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16TH CENTRAL HARDWOOD FOREST CONFERENCE

Proceedings of a Conference held at Purdue University, West Lafayette, IN
April 8-9, 2008

Edited by:
Douglass F. Jacobs, Purdue University
Charles H. Michler, U.S. Forest Service

Sponsored by:
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FOREWORD

The Central Hardwood Forest Conference is a series of biennial meetings that have been hosted by universities and research stations of the U.S. Department of Agriculture Forest Service in the central hardwood forest region in the Eastern United States. The objective of the conference is to bring together forest managers and scientists to discuss research and issues concerning the ecology and management of forests in the central hardwood region. This, the 16th Conference, includes presentations pertaining to forest regeneration and propagation, forest products, ecology and forest dynamics, human dimensions and economics, forest biometrics and modeling, silviculture and genetics, forest health and protection, and soil and mineral nutrition. The conference consisted of 64 oral presentations resulting in the papers published herein.

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REVIEW PROCEDURES

Manuscripts for oral presentations were assigned to one of the editors and peer-reviewed by at least two professionals unless otherwise indicated. Reviews were returned to authors to revise their manuscripts. Revised manuscripts were then submitted to the Northern Research Station, U.S. Forest Service for final editing and publishing.

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APPENDIX I: METRIC TO ENGLISH CONVERSIONS

Convert from:	To:	Multiply by:
bar (106 dynes/cm^2)	pound/inch^2 (psi)	14.5
bar (bar)	atmosphere (atm)	0.9869
calorie	British thermal units (Btu)	0.00397
Centigrade (C)	Fahrenheit (F)	1.80C + 32
centimeter (cm)	inch (in)	0.394
centimeters, square (cm^2)	inches, square (in^2)	0.155
centimeter, cubic (cm^3)	inches, cubic (in^3)	0.061
gram (g)	pound (lb)	0.002205
gram (g)	ounces (oz)	0.0353 (for water density)
grams/liter (g/L)	percent (%)	0.100 (in water)
hectare (ha)	acre	2.471
kilogram (kg)	pound (lb)	2.205
kilogram/hectare (kg/ha)	pound/acre	0.893
kilometer (km)	mile (mi)	0.621
kilometer, square (km^2)	miles, square (mi2)	0.386
kilometer, square (km^2)	acre	247.1
liter (L)	ounce (fluid oz)	33.8
liter (L)	quarts (qt)	1.057
liter (L)	feet, cubic (ft^3)	0.0353
liter/hectare (L/ha)	quarts/acre (qt/acre)	0.428
lux (Ix)	candle-foot^2 (ft-c)	0.0929
meter (m)	yard (yd)	1.094
meter (m)	feet (ft)	3.281
meter^2 (m^2)	feet2 (ft^2)	10.76
meter^2/hectare (m^2/ha)	feet2/acre (ft^2/acre)	4.356 (basal area)
meter^3 (m^3)	feet3 (ft^3)	35.31
meter^3 (m^3)	board feet, International 1/4"	287.4
meter^3/second (m^3/s)	gallons/second (gal/s)	264 (flow)
meter^3/hectare (m^3/ha)	feet^3/acre (ft^3/acre)	14.29
milligrams/liter (mg/L)	parts per million (ppm)	1.000 (in water)
millimeter (mm)	inch (in)	0.0394
ton (t) or megagram (Mg)	ton (U.S.)	1.102
ton/hectare (t/ha)	ton/acre (t/acre)	0.446

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FOREST REGENERATION AND PROPAGATION

STUMP SPROUTING OF OAK SPECIES IN THREE SILVICULTURAL TREATMENTS IN THE SOUTHERN APPALACHIANS

Chad J. Atwood, Thomas R. Fox, and David L. Loftis[1]

Abstract.—Harvesting practices in the southern Appalachians have been moving towards partial harvests, which leave some desired species as residuals after an initial harvest. This study investigated differences among two partial harvest treatments and a clearcut on oak stump sprouting in seven southern Appalachian hardwood stands. The sites were in southwest Virginia and east central West Virginia. The three silvicultural treatments consisted of a leave-tree (5 m^2 per ha), a shelterwood (12 to 14 m^2 per ha), and a silvicultural clearcut. Three permanent plots were randomly located in each treatment, inventoried and tagged prior to harvest. All tree species >5m in height were tagged and measured. Each stand was harvested during 1995-1998. During the summers of 2006 and 2007, the plots were inventoried and measurements were taken and recorded to quantify stump sprouting. Analysis of the data was performed using a z-test for comparing two binomial proportions: those that sprouted versus those that did not. Results show that the stumps in the clearcut had higher rates of sprouting than those in the leave-tree ($p<0.001$), which in turn had higher rates of sprouting than those in the shelterwood ($p=0.024$).

INTRODUCTION

The southern Appalachian region has long been known as a source for quality hardwood production. Oak (*Quercus* spp.) are the cornerstone species in this region (Appalachian Hardwood Manufactures 2007). However, harvesting methods and disturbance regimes in the Appalachians have changed over time, from mostly clearcutting and frequent wildfires to partial harvests and fire suppression (Yarnell 1998). Two common alternative silvicultural systems to a clearcut are a leave-tree and shelterwood. Both systems leave residual trees, which can influence stand regeneration (Loftis 1990, Miller and others 2006).

Oak reproduction originates from three sources: seedlings, advance regeneration, or stump sprouts. Stump sprouting has been found to be more important in this region than elsewhere (Cook and others 1996). The quality of trees which result from stump sprouts equal other forms of oak regeneration if stands are properly harvested and stump heights are kept low (Groninger and others 1998). Additionally, oak stump sprouts are often more competitive than the other two sources of regeneration. Stump sprouts have a large established root system which supports more rapid growth, and allows the sprouts to be more competitive. Newly established seedlings are frequently overtopped by faster-growing competitors (Larsen and Johnson 1998).

Site quality has been shown as an important factor determining regeneration success. In full-light conditions, shade-intolerant species, such as yellow-poplar (*Liriodendron tulipifera* L.), can out-compete oak stump sprouts on excellent sites (24m SI_{50}). Oak stump sprouting is most effective as a form of regeneration on fair to good sites (18 to 21 m SI_{50}) (Wendel and Trimble 1968). A stump's ability to sprout can also be affected by the silvicultural system. Those systems that leave residuals alter the regeneration conditions compared to systems that do not retain any trees.

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The leave-tree, also known as a deferment cut, is commonly used as a more aesthetically pleasing alternative to clearcutting. It is a two-age method in which a few individual stems (30 to 40 reserve trees per ha) are left for another full rotation, creating two distinct age classes (Nyland 2002). Logging damage is often a concern for these residuals as is epicormic branching and wind-throw (Smith and others 1989). These trees have also been shown to influence regeneration within a certain area surrounding them. Additionally, the open conditions lead to crown expansion in the residuals, which has been shown to be significantly different based on species (Miller and others 2006). This system relies on multiple sources of regeneration, including stump sprouts and advance regeneration, as well as seed from those residuals remaining in the stand.

The shelterwood relies on retaining enough individuals after the initial harvest to form a partial-light environment to favor the formation and accumulation of advance oak regeneration (Loftis 1990). This condition is designed to allow the oak, which are intermediately shade tolerant, to accumulate advance regeneration, while less shade-tolerant competitors cannot survive in these conditions. After 10 to 15 years the residuals will be removed and the advance regeneration should be large enough to out-compete fast-growing recently germinated shade-intolerant species.

OBJECTIVES

This paper looks specifically at stump sprouts as a form of oak regeneration in the southern Appalachians. The goals of this investigation were to quantify and compare the sprouting of different species of harvested oaks in the southern Appalachians and to determine if oak sprouting is influenced by species or silvicultural treatment.

SITES AND EXPERIMENTAL DESIGN

This investigation was conducted as part of a larger project known as the Southern Appalachian Silviculture and Biodiversity Project. This project was established in the early 1990s to study the effects of alternative silvicultural treatments in the southern Appalachians on even-aged oak dominated stands. Seven sites were established in Virginia and West Virginia (Fig. 1). The five sites in Virginia are located in the Jefferson National Forest. Three were located in the Ridge and Valley physiographic province (BB1, BB2, and NC) and two were located on the Appalachian Plateau (CL1 and CL2). The two West Virginia sites (WV1 and WV2) are located on the MeadWestvaco Wildlife and Ecosystem Research Forest (MWERF). The MWERF sites are located on the Appalachian Plateau. The sites were located in stands 60 to 120 years of age, growing on moderate slopes, and occupying a midslope position with a southern exposure. The site index base age 50 years, for upland oak, averaged 20 to 23 m. The plateau sites tended to be of higher site quality (Table 1).

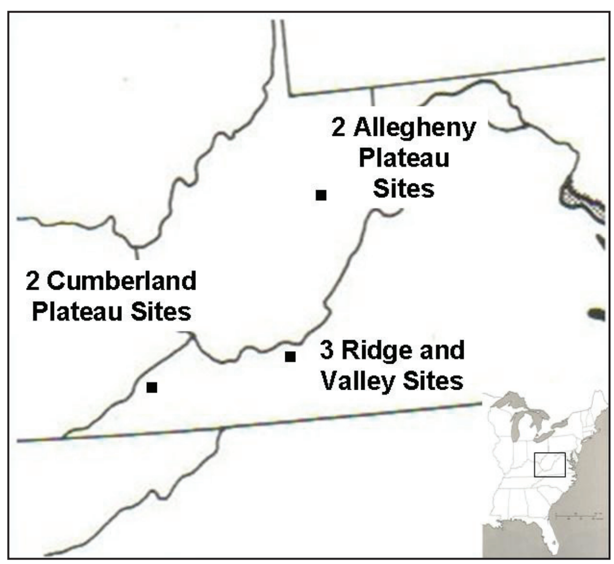

Figure 1.—Site locations.

Table 1.—Site Descriptions

Site	County, State	Oak S.I. 50yrs (m)	Age (yrs)	Year of Harvest Completions	Years Inventoried	Age at measurement (yrs)	QMD (cm)	Basal Area (m^2/ha)
BB1	Montgomery, VA	23	100	1995	1993,2006	11	19.8	25.5
BB2	Montgomery, VA	22	99	1996	1995,2006	10	18.2	26.8
CL1	Wise, VA	18	100	1998	1993,2007	9	21.2	29.2
CL2	Wise, VA	20	76	1998	1995,2007	9	19.2	29.1
NC	Craig, VA	18	62	1996	1995,2006	10	17.4	24.2
WV1	Randolph, WV	23	73	1997	1996,2007	10	17.8	35.2
WV2	Randolph, WV	24	63	1998	1997,2007	9	18.2	32.5

Adapted from Hammond 1997, Hood 2001, Lorber 2002.

Each site had seven treatments, but this investigation looked at three of those treatments: shelterwood, leave-tree, and silvicultural clearcut. Each treatment area was 2 ha. The shelterwood retained 12 to 14 m^2 per ha of residual basal area in dominant or codominant crown classes during the initial harvest. The residual overstory remained on site at the time of this inventory. The leave-tree left approximately 25 to 45 trees per ha totaling 5 m^2 per ha of basal area in dominant and codominant crown classes after the initial harvest; these trees will remain through the next rotation. The silvicultural clearcut removed all stems greater than 5 cm diameter at breast height (d.b.h.). The overall study design was a randomized complete block design with subsampling. Treatments were not replicated at each site; rather, each site served as a replication. In each 2-ha treatment there were three 24 m x 24 m tree plots. All of the tree plots were located at least 22 m from the treatment borders.

Prior to harvest all stems greater than 5 m tall were tagged and measured. The location of each tree within the larger tree plot was recorded. Plots were remeasured in 2006-2007, approximately 9 to 11 years after the initial harvest. Data were recorded on any sprouts present on the tagged stumps. The data taken were date, site, location, tree plot, tree number, diameter at ground per stump level (d.g.l.), d.b.h., height, and canopy class for each sprout on the stump. A z-test for comparing two binomial proportions was used with the categorical variable “sprout” or “no sprout” to compare the treatments (Ott and Longnecker 2001).

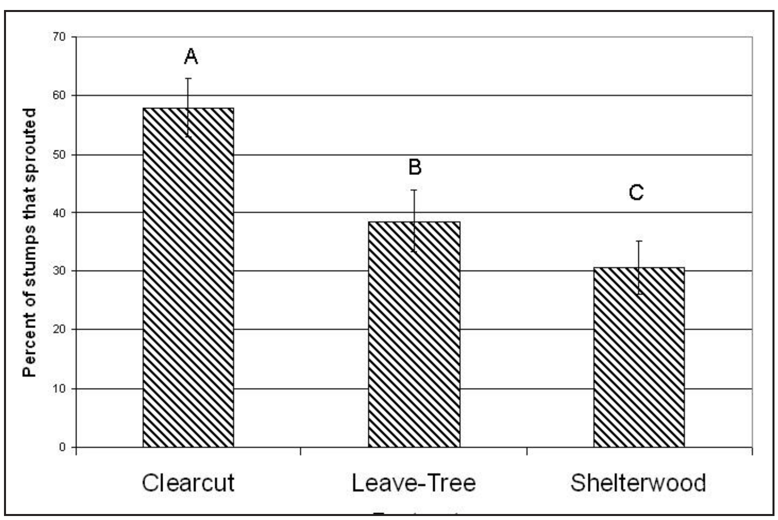

Figure 2.—Average percent of oak stumps that sprouted as affected by silvicultural treatment. Bars with different letters are significantly different (α=0.05).

RESULTS AND DISCUSSION

Data analysis revealed differences in stump sprouting among treatments (Fig. 2). Results indicated the clearcut was different with regard to number of stumps that sprouted from both the leave-tree and the shelterwood (p<0.01). The leave-tree and shelterwood were also different (p=0.025). Lorber (2002) indicated that post-harvest light conditions in the clearcut were significantly higher than the others, but similar in the shelterwood and leave-tree. Light levels could partially explain the difference between the clearcut and the other treatments, but not the difference between the leave-tree and shelterwood. These stands were of similar age and size (Table 1), so differences based on stump age or original tree diameter could not explain the different results, in contrast with similar studies (Johnson and others 2002).

A difference was found between physiographic provinces for each of the three treatments. The ridge and valley province sites had higher stump sprouting than the plateau sites for each treatment (Fig. 3). The plateau sites are of higher quality, but did not show greater stump sprouting ability contrary to other findings (Johnson and others 2002, Weigel and Peng 2002).

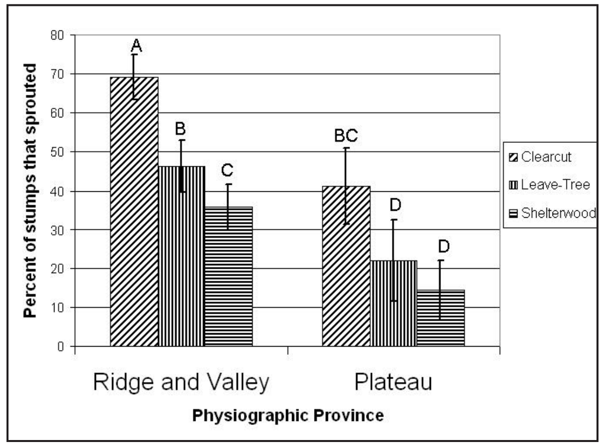

Figure 3.—Average percent of oak stumps that sprouted as affected by silvicultural treatment and physiographic province. Bars with different letters are significantly different (α=0.05).

Differences were also found among species within species groups by treatment (Fig. 4). White oak (*Q. alba* L.) sprouted the least of all oak species and was not affected by treatment. Overall sprouting percent was greatest in chestnut oak (*Q. prinus* L.). It was similar in the clearcut and leave-tree, but declined in the shelterwood. Sprouting percentages in scarlet oak (*Q. coccinea* Muenchh.), black oak (*Q. velutina* Lam.), and red oak (*Q. rubra* L.) were similar, and tended to fall between those of white oak and chestnut oak. All three species' sprouting tended to decrease in the leave-tree and the shelterwood compared to the clearcut.

The results of this study suggest that on fair to good quality sites in the southern Appalachians, silvicultural systems with residuals can significantly reduce the number of harvested oak stumps which sprout. Forest managers must take into consideration these findings when deciding which systems to use in the southern Appalachians, where stump sprouts are an important form of oak regeneration.

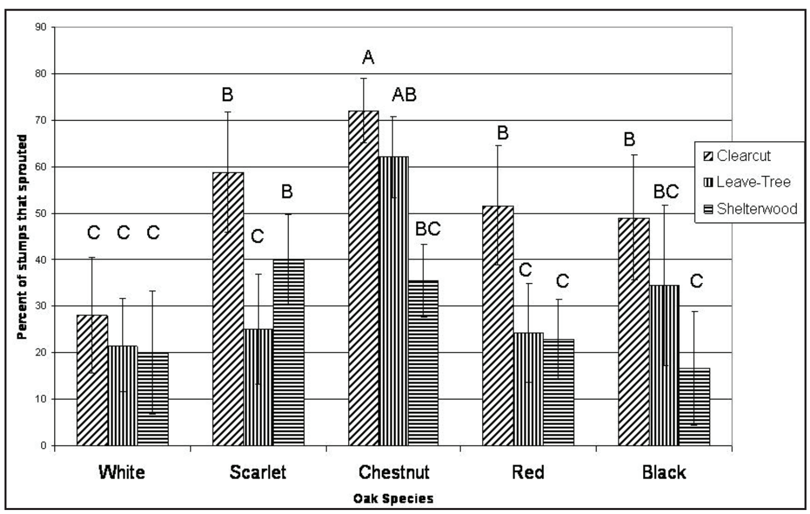

Figure 4.—Average percent of oak stumps that sprouted as affected by species and silvicultural treatment. Bars with different letters are significantly different (α=0.05).

ACKNOWLEDGMENTS

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GREENHOUSE AND FIELD PERFORMANCE OF GIANT CANE PROPAGULES FROM NATURAL AND PLANTED STANDS

William W. Brendecke and James J. Zaczek[1]

Abstract.—The objective of this study was to determine whether giant cane (*Arundinaria gigantea*) vegetative macropropagules of nine stock types could generate surviving culms to be used in restoration plantings in southern Illinois. In spring 2006, studies were conducted to compare culm production and survival of giant cane stock types that had varying rhizome morphology, collection origin (putative genotypes), collection location (natural stands or restoration planting), propagule type (bare rhizome, culms with attached rhizomes, and culm only) or length of storage in greenhouse and subsequent field plantings. Greenhouse survival of culm-only and culms with attached rhizomes stock types was poor, averaging 3.4 percent and 31.7 percent, respectively, and were not subsequently field planted. Rhizome morphology differed among bare-rhizome stock types. Greenhouse development and survival of culms from rhizomes averaged 60.1 percent and varied among the seven bare-rhizome stock types from 80.0 percent for a source collected from a restoration planting to 20.0 percent for a source from a natural stand that had been stored for 1 year. Greenhouse survival of culms from rhizomes of a similar origin (putative genotype) did not vary when collected from natural stands or restoration plantings. For surviving greenhouse propagules planted in the field, survival after 10 months was 64.4 percent and was independent of stock type. Field height, but not number of culms per rhizome, varied by stock type. Survival of culms from bare rhizomes throughout greenhouse and subsequent field plantings was 38.7 percent overall and depended on stock type.

INTRODUCTION

Giant cane (*Arundinaria gigantea* [Walt. Muhl.]) is a native North American bamboo species and component of floodplain forests and riparian areas within the southernmost Central Hardwoods Region. Its distribution encompasses 22 states in the United States (Marsh 1977). Extensive assemblages of cane are called canebrakes. Historic records indicate that canebrake ecosystems serve as important habitat for a variety of mammalian, avian, and reptilian species because of the protective nature that the dense culms provide (Platt and Brantley 1997, Platt and others 2001). For example, giant cane is important to provide nest habitat for the rare Swainson's warbler (*Limnothlypis swainsonii*) (Eddleman and others 1980). Giant cane also can serve as an effective riparian zone buffer for the protection of water quality (Schoonover and Williard 2003, Schoonover and others 2005).

Currently, canebrakes have been reduced to less than 2 percent of former abundance primarily by agricultural conversion, altered disturbance regimes and hydrological modifications of the floodplain (Marsh 1977, Noss and others 1995, Platt and Brantley 1997, Gagnon 2006, Stewart 2007). Noss and others (1995) suggest that the development of conservation strategies and management initiatives will be needed to restore these critically endangered ecosystems.

Giant cane has proven to be more difficult to propagate than other members of the bamboo family (Feeback and Luken 1992, Platt and Brantley 1993). Natural flowering and subsequent seed production

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Table 1.—Stock type origin, source, and date of collection and planting in the greenhouse for seven rhizome-only stock types used in greenhouse and field plantings[1]

Stock type	Rhizome number	Origin (putative genotype)	Collection source location	Dates collected	Dates planted 2006
BR05	40	Bellrose(BR)	Natural stand BR	03/25/05	03/08
BR06	32	Bellrose(BR)	Natural stand BR	02/16/06	03/07
BW06	40	Bluewing(BW)	Natural stand BW	03/28/06	03/29,04/06
BulkRF06	40	BR and HB	Rose Farms (RF) planting	02/23/06	03/08,03/23
UCRF06	40	Upper Cache River(UC)	Rose Farms (RF) planting	02/23/06	03/23
BRRF06	39	Bellrose(BR)	Rose Farms (RF) planting	04/05/06	04/11
HBRF06	40	Hickory Bottoms(HB)	Rose Farms (RF) planting	04/05/06	04/11

[1] To summarize, stock type codes indicate the origin from its original natural stand (if known) with the first two letters, whether the stock had been previously established in a 2001 planting at Rose Farms (designated by RF, if applicable), and the year the stock was collected for planting in the current study (either 05 or 06).

are irregular and unpredictable, and appear linked to age and site conditions, but specific details are not known (Gagnon 2006). Reproduction of giant cane and most bamboo is primarily vegetative, indicated by the spreading growth patterns of rhizomes and new culm shoots (Farrelly 1984, McClure 1993). Large-scale canebrake restoration is challenged by the lack of available planting stock and inadequate field establishment techniques (Feeback and Luken 1992, Sexton and others 2003, Hartleb and Zaczek 2007). Vegetative propagation using large clumps of rhizomes in soil with attached culms has shown to be a useful method (Dattilo and Rhoades 2005), but field-scale canebrake plantings with this method would be both expensive and resource limiting (Datillo and Rhoades 2005, Hartleb 2007). Propagation using smaller and more easily handled rhizome sections has shown promise in field-scale canebrake establishment (Hartleb 2007, Hartleb and Zaczek 2007).

Understanding factors that influence the propagation and field establishment of giant cane will help restore canebrake ecosystems to the landscape. Toward this goal, the objectives of this study were to determine if bare rhizomes from four origins of giant cane (putative genotypes), two collection sources (natural stands or plantings), and two storage times differ in their morphology, culm production ability, and survival and growth in greenhouse and subsequent field plantings after one growing season. Additionally, this study compared the survival and growth of culms without attached rhizomes and culms with attached rhizomes.

METHODS

There were seven stock types using bare rhizomes as propagules (Table 1). These rhizomes ultimately arose from four origins (putative genotypes because of giant cane's tendency to spread vegetatively) referred to as Upper Cache River (UC; Johnson County, IL), Hickory Bottoms (HB; Pulaski County, IL), Bluewing (BW), or Bellrose (BR). Rhizomes were dug from two collection sources (natural stands or restoration plantings). There were two different naturally established stands of giant cane (BW and BR, located about 1.5 km apart) and two adjacent 5-year-old giant cane plantings, a source collectively referred to as Rose Farms (RF). In all, seven bare-rhizome stock types were used (Table 1), that were various combinations of origin and collection source (indicated by letter codes) and collection year (indicated by either 05 or 06). Additionally, there were two other stock types using culm only and culm with attached rhizome pieces.

All collections were dug in early spring of 2006 except for Bellrose 2005(BRZ05), which was dug in early spring of 2005 from a natural giant cane stand on The Frank Bellrose Waterfowl Preserve in Pulaski County, IL, and stored under refrigeration until the spring of 2006. Three stock types came from this waterfowl preserve.

The other four stock types were dug from an experimental planting site established in 2001 at the Rose Farms, owned and managed by The Nature Conservancy. Giant cane rhizomes at RF had origins from BR, HB, and UC. The final RF stock type was a bulk collection of rhizomes from HB and BR in unknown proportions.

The bulk collection of stock type BulkRF06 rhizomes and stock type UCRF06 were dug with hand shovels (for dates see Table 1). A backhoe was used to dig the remaining stock types (Table 1). Rhizomes were shaken free of soil, cut to a range of 20 to 44 cm ($\bar{x}$ =28.9 cm) in length, and placed in white plastic bags to prevent drying. Attached culms, except for the culm only and culm with attached rhizome stock type described below, were removed before storage. Bags were then transported to the Tree Improvement Center (TIC) greenhouse at Southern Illinois University (SIU) where rhizomes were rinsed with tap water and any damaged sections were removed. Rhizomes were then placed in bags with peat-moss and stored at approximately 4 °C until measured and planted.

Before greenhouse planting, each rhizome was tagged with an identification number and data were collected on length (to the nearest cm), number of nodes and buds, and diameter (0.1 mm). Internode length (cm) was determined by dividing the length by the number of nodes. Rhizome diameters are the geometric mean of minimum and maximum diameters taken with a caliper at a mid-rhizome internode (Husch and others 1972). Rhizomes were trimmed to remove damaged sections, including damage from extended storage on BR05, resulting in a range of lengths (20 to 44 cm) in the rhizome only stock types.

Rhizomes were planted vertically with the distal end up in D40 Deepot containers (Stuewe & Sons, Inc., Corvallis, OR) measuring 25.0 cm in length and 6.4 cm in diameter and filled with Promix BX potting medium (Premier Horticulture Inc., Quakertown, PA). For rhizomes shorter than 27 cm, rhizomes were planted not extending to the container bottom and were left to protrude from the surface of the potting medium ~2 cm. Longer rhizomes were planted touching the bottom and any remaining portion was left exposed above the potting medium. On the date of planting (Table 1), potted rhizomes were watered and placed on greenhouse benches under intermittent mist at a frequency of 12 seconds every 6 minutes during daylight hours. After at least 1 month in the greenhouse and prior to field planting, data were collected on survival (those rhizomes that produced a surviving culm), number of culms, and height (cm) of tallest culm.

Stock types for culms alone (C) and culms with rhizome (C+R) were collected with shovels on April 5, 2006 at Rose Farms. Fifty-six C propagules were separated from their attached rhizome at a rhizome node while maintaining their associated roots were maintained (Fig. 1). Fifty-eight C+R propagules with rhizomes ~10 cm long with at least one live bud were collected. In both cases, original height of the culms (40 to 60 cm) was maintained and the propagules were placed into white trash bags to prevent drying and

Figure 1.-Image of culm and rhizome (C+R) indicating the location where culms were detached from rhizomes (green dashed line) for culm-only (C) propagules.

taken to the TIC greenhouse at SIU. The C and C+R propagules were planted (April 11-13, 2006) in CL-300 pots 17 cm wide by 18 cm deep (Nursery Supplies, Inc. Chambersburg, PA), watered, and maintained under mist as described previously.

After 6 to 11 weeks in the greenhouse, rhizomes that had maintained surviving culms (N=163) were field planted (May 24, 2006) on the Cypress Creek National Wildlife Refuge. The field site was an abandoned agricultural field located within 1 km of an existing natural giant cane stand (HB). Propagules were machine planted in a completely random design using a Whitfield (Mableton, GA) tree planter towed behind a tractor. Newly grown plants were removed from the D40 pots and planted with the top of the potting media approximately 1 cm below the surface of the ground at 1.5-m distances within a row (seven rows total). Rows were spaced 3.0-m intervals apart. The soil is in the Petrolia series with taxonomic class being described as fine-silty, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquepts (Natural Resource Conservation Service 2007).

Chi-square analysis was used to test for survival differences among treatments (Preacher chi-square online software 2001). One-way analysis of variance was used to test for differences among treatments for continuous variables and correlation analyses were used to test for significant relationships among variables (SPSS 15.0.0., SPSS Inc., Chicago, IL). The significance level was set at α=0.05 for all tests.

RESULTS

Rhizome Characterization

Comparisons of preplanting rhizome morphology among the seven stock types showed that rhizomes differed in diameter ($p<0.001$), number of nodes ($p<0.001$), length of internodes ($p<0.001$), number of buds ($p<0.001$), but not ($p=0.089$) length (Table 2). The range of diameters and internode lengths varied by approximately twofold across stock types and in many cases were distinct when comparing stock types that arose from natural stands versus plantings. Comparing sources grouped as being collected from natural stands vs. plantings (Table 3), rhizomes from plantings were smaller in diameter ($p<0.001$) and were shorter ($p=0.039$), but had more nodes ($p<0.001$) and buds ($p<0.001$), and shorter internode length ($p<0.001$) than those arising from natural giant cane stands.

Table 2.—Mean length, diameter, internode length, and number of nodes and buds for the seven rhizome-only stock types prior to planting in the greenhouse

Stock types	Number of rhizomes	Rhizome diameter (mm)	Rhizome length (cm)	Internode length (cm)	Nodes per rhizome	Buds per rhizome
BR05	40	11.42 a[1]	29.9	4.2 a[1]	7.6 c[1]	3.7 c[1]
BR06	32	10.63 a	29.8	3.1 b	10.3 b	8.0 b
BW06	40	8.26 b	29.4	2.7 bc	11.9 ab	7.2 b
BulkRF06	40	6.55 c	30.0	2.3 cd	14.0 a	9.6 ab
UCRF06	40	6.53 c	28.1	2.1 d	14.0 a	9.8 ab
BRRF06	39	5.46 d	27.0	2.2 cd	13.4 a	9.1 ab
HBRF06	40	5.11 d	28.3	2.2 cd	14.2 a	10.9 a

[1]Means with the same letter within a column are not significantly different according to Tukey's HSD at p=0.05

Table 3.—Mean length, diameter, and the number of nodes and buds combining rhizomes from sources collected from three natural stands or from four field plantings prior to potting rhizomes in the greenhouse

Collection source	Rhizome length (cm)	Nodes per rhizome	Buds per rhizome	Rhizome diameter (mm)
Plantings	28.4 b[1]	13.9 a[1]	9.9 a[1]	5.91 b[1]
Natural stands	29.7 a	9.9 b	6.1 b	10.07 a

[1]Means with the same letter within a column are not significantly different according to Tukey's HSD at p=0.05.

Table 4.-Pearson correlation coefficients and p-values (2-tailed) for morphological traits of bare rhizomes for all sources (N=271)

		Internode length	Rhizome Diameter	Nodes per rhizome	Buds per rhizome
Rhizome length	Pearson r	0.156	0.137	0.037	0.197
	P=	0.010	0.024	<0.001	0.001
Internode length	Pearson r	1	0.621	-0.776	-0.686
	P=		<0.001	<0.001	<0.001
Rhizome Diameter	Pearson r		1	-0.463	-0.428
	P=			<0.001	<0.001
Nodes per rhizome	Pearson r			1	0.784
	P=				<0.001

Correlation analysis showed significant relationships among all rhizome morphological characteristics (Table 4). There were strong positive relationships between internode length and rhizome diameter, and between the number of nodes and buds. Conversely, numbers of buds were negatively correlated with rhizome diameter and internode length.

Propagule Planting

Greenhouse Phase

The C stock type had only 3.7 percent survival. None of the originally existing planted culms from the C+R stock survived. However, 30 percent of the C+R stock formed new culms from buds on the attached rhizomes. Consequently, neither of these stock types was field planted because of low numbers of surviving plants for comparisons.

For bare rhizome stock types, greenhouse survival (or rhizomes that produced surviving culms at the end of the greenhouse growing period) was dependent on treatment and varied greatly when all seven stock types (chi-square; p=<0.001) were compared (Table 5). For other specific comparisons, survival depended on year of collection (storage duration) for those rhizomes collected from a common location in 2005 vs. 2006 (BR05 vs. BR06, p=0.007), stock type for those collected only in 2006 (chi-square; p=0.038), and putative genotype for those of known single origins collected from plantings only (chi-square; p=0.04). Survival was independent of origin for those collected from natural stands (BR06 vs. BW06, p=0.08). Concerning rhizomes from similar origins, survival was also independent of being collected from planted vs. natural stands (BRRF06 vs. BR06, p=0.747).

Table 5.—Greenhouse survival, number of culms per rhizome, and height of tallest culm of the seven bare-rhizome stock types after the greenhouse growing period and prior to field planting

Stock types	Survival (%)	Number of culms	Height of tallest culm (cm)
BR05	20.0	1.3 b[1]	35.8 a[1]
BR06	50.0	1.7 ab	34.5 a
BW06	70.0	2.1 ab	22.0 bc
BulkRF06	75.0	2.0 ab	21.1 bc
UCRF06	70.0	2.4 a	27.2 ab
BRRF06	53.8	2.0 ab	8.4 d
HBRF06	80.0	2.8 a	12.5 cd

[1]Means with the same letter within a column are not significantly different according to Tukey's HSD at p=0.05.

After 6 to 11 weeks in the greenhouse, height of the tallest culm and culm number differed (p<0.001; p=0.004, respectively) among stock types (Table 5). However, when stock types were grouped by collection source (natural stand vs. plantings), rhizomes from natural stands produced fewer (p=0.021) culms ($\bar{x}$=1.9) than those collected from plantings ($\bar{x}$=2.3), but were taller (27.9 cm vs. 17.7 cm respectively, p<0.001).

Since there were differences in morphology among stock types, analyses were completed for each source (Table 6) to identify whether original rhizome characteristics differed between rhizomes that produced live culms versus those that did not (no culm). For a limited number of comparisons by stock type, surviving propagules arose from rhizomes that tended to be larger in diameter, had more buds, and were shorter in length than those that did not produce a living culm (Table 6).

Field Phase

For those rhizomes that produced culms in the greenhouse trial and were planted outdoors (n=105), field survival after one growing season (Table 7) was independent of stock type (chi-square; p=0.674) and year

Table 6.—Rhizome length, diameter, and number of buds for rhizomes with live culms (culms) and without live culms (no culms) of seven stock types after growing 6 to 11 weeks in the greenhouse

Stock type	Rhizome Length(cm)		Buds per Rhizome		Rhizome Diameter(mm)	
	Culm	No culm	Culm	No culm	Culm	No culm
BR05	29.0	30.1	6.0 *[1]	3.1 *	11.21	11.47
BR06	29.2	30.3	9.1	6.9	11.23	10.03
BW06	29.1	30.2	8.3 *	4.7 *	8.40	7.95
BulkRF06	30.5	28.5	10.0	8.5	6.34 *[1]	7.17 *
UCRRF06	27.7	28.9	10.4	8.4	6.24 *	7.19 *
BRRF06	25.3 *[1]	28.9 *	9.6	8.6	5.47	5.44
HBRF06	26.6 *	35.4 *	10.9	10.8	5.06	5.30

[1]Means along a row between culm and no culm producing rhizomes within a characteristic with an (*) are significantly different at p=0.05.

Table 7.—Percentage survival, number of culms, height of the tallest culm for greenhouse-grown, field-planted propagules; and overall survival percentage (a product of greenhouse survival and field survival) of initial rhizomes surviving both greenhouse and field planting with live culms from seven stock types 10 months after field planting

Stock types	Number field planted	Field survival (%)	Number of culms	Height of tallest culm (cm)	Overall survival (%)
BR05	8	75.0	2.3	19.0 a	15.0
BR06	16	75.0	2.5	15.9 ab[1]	37.5
BW06	28	64.3	2.6	13.0 bc	45.0
BulkRF06	30	66.7	2.9	9.7 cde	50.0
UCRF06	28	67.9	3.2	10.7 cd	47.5
BRRF06	21	47.6	2.4	6.2 e	25.6
HBRF06	32	56.3	2.9	7.2 de	50.0

[1]Means with the same letter within a column are not significantly different according to Tukey's HSD at p=0.05.

of collection (BR05 vs. BR06) (chi-square; p=0.617). For those rhizomes collected only in 2006, survival was independent of stock type (chi-square; p=0.207). The percentage of rhizomes that produced culms that survived both greenhouse and field planting (Table 7) was dependent on stock type (chi-square; p=0.005) when the seven stock types were considered. However, survival of culms was independent of collection source (chi-square; p=0.061) when natural stands were compared with plantings.

Height of the tallest culm differed among stock types after one growing season (p<0.001). Rhizomes collected from natural stands tended to be taller (p<0.001), but had similar numbers of culms (p=0.195) in comparison to those collected from plantings (Table 8).

Table 8.—Number of culms and height of tallest culm 10 months after field planting combined across rhizomes collected from three natural stands and four field plantings (n=105)

Collection Source	n	Number of culms[1]	Height, tallest culm[1] (cm)
Natural stands	36	2.5	15.0 a
Plantings	69	2.9	8.7 b

[1]Means with the same letter within a column are not significantly different according to Tukey's HSD at p=0.05.

DISCUSSION

We found less than 4 percent of culm-only (C) propagules still had live culms after 6 weeks in the greenhouse; C propagules did not produce any new culms. Platt and Brantley (1993) reported 40 percent of trimmed culm-only segments had produced new culms, but the new culms were smaller and were produced later than their trimmed culm segments with attached rhizomes. In the current study, the C+R propagules had the original culms die back, but 30 percent did produce newly sprouted culms. Since the original culm of the C+R treatment died back, we do not recommend using intact culms or intact culms with untrimmed attached rhizomes for macropropagules.

Although we did not determine whether new rhizomes were formed from culm-only segments, we observed more than 3,000 pieces (approximately 20 to 50 cm in length) of excavated rhizomes with attached culm segments and saw that new rhizomes did not emanate from bases of culms, but rather from existing rhizomes. This observation suggests that, although culm-only segments may stay alive and even produce new culm shoots, they may not produce the new rhizomes that are important in field establishment and the spread of canebrake communities. Platt and Brantley (1993) did obtain delayed production of shorter than average culms from culm-only stock, but it was unclear from their report whether or not these new culms arose from newly formed rhizomes or from remnant culms without new rhizome formation. Others have concluded that vegetative propagation of temperate bamboo species by culm segments is ineffective (Farrelly 1984, McClure 1993). Our experience with culm-only segments was similar and suggests that if culm segments are to be used, a portion of rhizome should remain attached.

Before attempting to understand giant cane's greenhouse- and field-growth performance, we need to recognize the preliminary "traits" each of the sources have, and how those compare with one another. For the most part, rhizomes from planted stands were smaller in diameter, and had more nodes and buds than those from natural stands. This result may in part reflect the fairly recent establishment of these (approximately 5 years previously), which are still developing compared to the natural stands. Although of unknown age, the natural stands were older (>5 years), more well developed, and had larger aboveground culms. Our results showed that the culm heights were greater when generated from rhizomes collected from relatively undisturbed and established natural stands versus more recently planted stands.

Size potentials of giant cane appear linked to age and site conditions, but specific details are not known (Gagnon 2006). Repeated reduction of culms and leaves by disturbance depletes rhizome stores (Hughes 1966, Marsh 1977). Hughes (1951) noted that appreciable changes in rhizome development from seedlings precede any substantial changes in height. Although the phenotype of the rhizomes in the current study may be related to their growing environment and the age of the stand, phenotype is also influenced by origin (genotype) and ontogeny of the stand. We can see this influence (Table 2) when comparing BRRF06 and BR06. Both stocks originated from Bellrose, but planted BRRF06 was smaller in diameter, with more nodes, and buds compared to the more established natural stand BR06.

The other natural stand source with Bellrose origin (BR05) had differing morphology even compared to BR06. The BR05 source tended to be most morphologically distinct among all sources with fewer nodes and buds, and longer internodes. It also had a larger diameter than all but the BR06 source, which had common origins from the same natural stand. The disturbance of digging rhizomes in 2005 at Bellrose may have stimulated formation of more newly formed rhizomes with differing morphology which were collected in 2006 when digging in the same general area.

Stock type influenced the number of culms generated from rhizomes in the greenhouse. But once those rhizomes with living culms were outplanted, the stock types did not differ in survival in response to field conditions. Considering rhizomes collected only from plantings, origin (putative genotype) influenced production and survival of culms. Differences in culm shoot production among origins have been previously reported (Sexton and others 2003). However, in the current study, survival was not significantly affected—although nearly so ($p=0.08$)—by origin for those collected from natural stands.

If macropropagation techniques are to be employed for large-scale restoration initiatives, knowledge about giant cane's handling and storage constraints would help managers decide on size and scope of plantings. In the current study, year-long refrigerated storage negatively affected survival. It has been recommended that bamboo be collected in the early spring (McClure 1993, Bell 2000) and be planted as soon as possible after digging (Farrelly 1984). Production of any surviving giant cane propagules from rhizomes subjected to year-long storage had not been previously reported although shorter-term storage of 1 month under refrigeration was shown not to be detrimental to survival or production of living shoots (Hartleb 2007). A flexible window of time for collection coupled with extended storage of giant cane could be beneficial to meet management constraints that are affected by available labor, and favorable soil moisture conditions for digging and field planting.

Bell (2000) recommends that for vegetative propagation, cuttings should come from rhizomes no more than 2 years old. In the current study, although rhizome age was undetermined, those from the 5-year-old plantings were more likely to have been younger and ontogenetically more juvenile than those from natural stands of unknown age. As evidence, rhizomes from the plantings tended to be smaller in diameter with shorter, more slender culms. Rhizomes from younger planted stands did have higher survival in the greenhouse; having a higher number of buds may lead to a higher probability of a bud to produce a culm.

It has been recommended that for monopodial bamboo, rhizome propagules be yellowish, 38 to 102 cm long, with at least 10 good buds (Farrelly 1984). In the current study using containers, we used rhizomes that were generally smaller (20 to 44 cm). In our study, surviving rhizomes also tended to be shorter, which differed from a previous experiment using more widely contrasting sizes without containers (Sexton and others 2003), but was similar to that found by Hartleb (2007), who used rhizomes of more similar length using the same type of containers. This difference may be attributed to longer rhizomes having a larger portion of exposed giant cane protruding from the containers which may desiccate the rhizomes when the mist system was off during nighttime hours (Hartleb 2007). Consequently, in containers, long rhizomes are not desirable, but characteristics such as larger diameter and more buds are important for culm production.

We used D40 Deepot containers to meet planting constraints when using machine tree planters. Tree planters cut an approximate 10 cm wide slit in which to plant stock. Within these constraints, using large potted rhizomes is not feasible. Hartleb (2007) showed greenhouse rearing using D40 Deepots prior to field outplanting produced no survival advantage to direct field planting of rhizomes. We also found no significant advantage of growing propagules in the greenhouse with these methods. Planting rhizomes directly in the field required less effort, time, and resources than initial growing in the greenhouse.

Potential culm size (height and diameter) is a reflection of available food reserves in the rhizomes (Bell 2000). Li and others (1998) noted a conspicuous decrease of carbohydrate concentration in the rhizomatous *Phyllostachys pubescens* with development of new shoots. While using longer rhizomes provides more available non-structural carbohydrates, this advantage is lost with container-grown propagules because the exposed section of the rhizomes dries out, perhaps making these carbohydrates unavailable for culm growth. If greenhouse planting utilizing D40 Deepots is to be used for rhizomes, we recommend that the length of the rhizome exposed be limited to a maximum of 7 to 12 cm above the surface of the potting medium and that any exposed roots be removed to reduce surface area.

SUMMARY

This study demonstrated that bare rhizomes can be used to generate greenhouse-grown giant cane plants for use in subsequent field plantings. Intact rooted culms and culms with rhizomes are not recommended for use, nor are bare rhizomes stored 1 year. Our trials stress the importance of stock type to survival and growth of planted giant cane. Both origin (putative genotype) and stand development (collection source) influence survival and growth of culms generated from rhizomes. Obtaining stock directly from natural stands tends to produce taller culms although overall survival was similar to rhizomes collected from plantings. Although it was shown that rhizomes could produce surviving culms even after 1 year in storage, this extended storage period greatly reduced the rhizome viability and is not recommended.

While natural stand rhizomes are larger in diameter and provide taller initial culms, they do not provide the same number of buds per unit length as a plantation source. Having buds that form both new culms and new rhizomes is desirable and choosing propagules with fewer buds lowers any chances of that happening. Macropropagation success in containers can increase with rhizomes that have more buds per unit length and greater diameter.

Developing field-expedient, operationally feasible giant cane restoration techniques would help promote the species' return to sites it once occupied. Propagation by rhizomes has shown to be a viable option, but inadequate knowledge as to the physiological ecology of the species and limited availability of planting material remain a challenge. Continued development of regeneration techniques for this valuable species will provide the knowledge needed for managers and ecologists to restore canebrake ecosystems to the landscape.

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GRAFTING INFLUENCES ON EARLY ACORN PRODUCTION IN SWAMP WHITE OAK (*QUERCUS BICOLOR* WILLD.)

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Abstract.—Early fruiting of swamp white oak planting stock has been observed. The potential to exploit this trait for wildlife enhancement purposes was evaluated in a grafting study. Scions from both precocious and non-precocious ortets were grafted onto a series of related seedling rootstock sources. Acorn production was recorded through age 4 years. Acorn productivity of the grafts was identical to their ortet rankings for cumulative acorn production over a 5-year period when graft productivity was standardized on a trunk cross-sectional area basis. There was no significant scion x rootstock family interaction for acorn production. However, significant scion and rootstock effects were detected for both stem diameter and number of acorns produced per grafted tree. No single rootstock source proved to be superior in terms of acorn production. Based on these results, it is anticipated that precocious tree genotypes can be readily multiplied by grafting, and high acorn productivity can be maintained via this grafting approach. Subsequent establishment of grafted seed orchards for the production of precocious seedling planting stock for reforestation purposes should be possible, depending upon the heritability of this important trait.

INTRODUCTION

Swamp white oak (*Quercus bicolor* Willd.) is an important mast species, producing medium-sized acorns that are highly desirable to wildlife in both upland and bottomland forests. Dey and others (2004) reported wide variation in both precocity and acorn productivity for swamp white oak within their bottomland oak plantings. They reported that 3.5 percent of the saplings started producing acorns in as few as 3 years from seed. This early fruiting trait is highly desirable and should serve as the basis of selection when individuals are being identified to deploy in bottomland plantings for wildlife enhancement purposes. Farmer (1981) suggested that selecting for fecundity within a population of grafted white oak (*Q. alba* L.) clones should be successful since more than 50 percent of the variance in seed production was associated with clonal origin, regardless of tree size. This strategy is in contrast to other clonal seed orchard programs that focus on the production of genetically improved oak seed stocks for timber purposes. For such programs, seed production within the orchard can be highly irregular from clone to clone because inclusion within the orchard is based on selection for a series of timber traits rather than fruiting capacity (Kleinschmit 1986).

Little information is available documenting the heritability of precocity and acorn production in swamp white oak. In addition, we have found no information on how scion or rootstock source may affect the precocity or productivity of grafted swamp white oak trees. In many fruit crops, the use of specific rootstock sources can result in earlier fruiting and increased yields (Rom and Carlson 1987). For a grafting program to be successful as part of an applied tree improvement program, the grafted ramets should exhibit similar patterns of precocity as the selected ortets, and any rootstock effects on precocity should be clearly defined.

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Vegetative propagation of swamp white oak by use of softwood cuttings is difficult (Fishel and others 2003), especially in comparison to other native oak species such as northern red oak (*Q. rubra* L.). To our knowledge, no tissue culture protocols have been developed for this species to date although Gingas (1991) did have limited success in culturing somatic embryos of this species derived from male catkins. However, the resulting plantlets failed to acclimate in the greenhouse.

Delayed graft compatibility in *Quercus* has been observed, especially for species in the Lobatae sub-genus (Santamour and Coggeshall 1996). However, few such problems appear to be associated with species in the white oak, or *Quercus* sub-genus. To illustrate this fact, of the 252 valid oak cultivar names listed by McArdle and Santamour (1985, 1987a, 1987b), a total of 224 are from the *Quercus* sub-genus while only 28 represent species in the Lobatae sub-genus. Expression of graft incompatibility can be delayed up to 7 years after grafting in *Q. rubra* (Coggeshall 1996). Symptoms include significant scion overgrowth of the rootstock, vigorous suckering, and precocious flowering (Coggeshall 1993). Our experience in grafting species of the white oak sub-genus led us to expect few if any delayed incompatibility problems for at least the first 10 years following grafting.

OBJECTIVES

Our objectives for this study were to determine if grafted swamp white oaks exhibit a similar trend in precocity as their selected ortets and to determine any rootstock effect on fruiting in grafted swamp white oaks.

MATERIALS AND METHODS

In fall 1995, acorns were collected from a single swamp white oak tree in Boone County, MO. Acorns were sent to the Forrest Keeling Nursery in Ellsberry, MO to produce both 1-0 bareroot seedlings and their patented Root Production Method (RPM®) seedlings. In spring 1997, seedlings were planted on an upland ridge with deep loess soils at the University of Missouri Horticulture and Agroforestry Research Center in Howard County, MO. Initial tree spacing was 3 m within row and 6.1 m between rows. Within-row vegetation was controlled with periodic application of glyphosate from 1997 through 2002 while the between-row tall fescue sod was periodically mowed. Individual tree height and basal diameter as well as annual acorn production were measured from 1997 through 2003.

Acorns were collected from six precocious trees and were sown in the fall of 2001 following the RPM® method (Lovelace 1998). These six parent trees were classified as being precocious based on their capacity to produce a minimum of 200 cumulative acorns each by age 7 (Table 1). In this method, acorns were sown on the surface of potting medium within 38 x 38 x 10.2 cm deep trays (Anderson Die and Manufacturing Co., Portland, OR). Then trays were stacked, placed within a closed polyethylene bag, and stratified for 3 to 4 months at 2.2 °C within a walk-in refrigerator. Trays were moved to a heated greenhouse in March 2002. One-flush germinants were shifted to Anderson™ (9.2 x 9.2 x 12.7 cm) plant bands, and then to 6.2-L pots (15 x 15 x 41 cm) to produce 1-year-old, three-flush container-grown seedlings during the 2002 growing season. Seedlings were overwintered outdoors under 0.63-cm thick closed-cell white polyethylene foam covered by a single layer of 4-mil white polyethylene sheeting.

In January 2003, scionwood was cut from five precocious and three non-precocious trees from the study established in the spring 1997. A total of 192 whip-and-tongue grafts were made in the greenhouse in early spring of 2003 on the 6.2-L potted rootstocks produced in 2002. Grafting success rates exceeded 90

Table 1.—Stem diameter and number of acorns produced for 10 swamp white oak trees (ortets) used as sources for either scionwood or acorns for production of rootstocks

Ortet Number[1]	Stock type	Fall 2002 d.b.h. (cm)	First year for acorns	Cumulative no. acorns from 1999-2003
1	Bare-root	8.6	1999	593
2	RPM	6.4	1999	202
3	Bare-root	7.3	2000	511
4	Bare-root	7.4	2000	180
5	RPM	7.3	2000	235
6	Bare-root	6.8	2000	230
7	Bare-root	7.8	2000	227
8	RPM	8.2	2001	126
9	RPM	7.3	2002	14
10	RPM	6.1	>2002	0

[1]Ortet #1 through #7 were considered to be precocious and ortet #8 through #10 non-precocious.

percent for all scion x rootstock combinations. Successful grafts were moved outdoors in May 2003 to a shade house (55 percent shade) and received daily overhead irrigation. A total of 127 grafts representing eight scion x six rootstock (half-sib family) combinations were planted in a random design during October 2003 on a north-facing slope at the Horticulture and Agroforestry Research Center. Grafts were planted on a Menfro silt loam soil at 3.7 x 4.6-m spacing within a 0.2-ha plot with no obvious site variation. Grafts have received annual spot weed control with glyphosate and periodic mowing to control grass competition.

In September 2006, survival, diameter at breast height (d.b.h.; cm), and number of nuts were recorded for each graft. In addition, the trunk cross sectional area (TCSA) of each graft based on d.b.h. was calculated. These data were subjected to analysis of variance for a completely randomized design. As a result of unbalance, Type III sums of squares were used to determine if differences existed among scion, rootstock, and scion x rootstock at the 5-percent level. Fisher's unprotected least significant differences were calculated to separate statistically different means at the 5-percent level.

RESULTS AND DISCUSSION

The RPM® seedlings in the study established in 1997 were larger in basal stem diameter (11.2 vs. 8.3 mm) and stem height (1.1 vs. 0.5 m) than the bare-root seedlings at outplanting. It is unknown what effect size may have; however, recent advances in the RPM® technology now produce much larger swamp white oak seedlings such as those used by Dey and others (2004) in their bottomland reforestation project. Although the RPM® seedlings in our study maintained a slight size advantage over the bare-root seedlings, we found no differences between stock types as to the age when trees began producing acorns (Table 1). Lack of statistical differences between stock types for cumulative total acorn production from 1999 through 2003 may in large part be because of two exceptionally productive trees established as bare-root seedlings (ortet #1 and #3). Neither fertilization nor irrigation increased acorn production of either stock type on this excellent oak site (data not shown). The wide variation in acorn precocity and production found among the 64 half-sib seedlings grown on a deep soil with adequate soil moisture and nutrients suggests that fruiting is likely under strong genetic control.

Table 2.—Stem diameter, acorn production and the number orf acorns per TCSA produced by 4-year-old ramets grafted with scionwood of the eight ortets described in Table 1

Scion wood Ortet number[1]	No. of ramets	Percent bearing	Acorns per grafted ramet		Average d.b.h. (cm)	Acorns/TCSA (no./cm^2)
			Average	Maximum		
1	21	100	41	126	2.8	1.55
2	16	100	33	77	3.3	0.91
3	22	96	75	186	2.8	2.59
6	12	100	57	112	3.4	1.52
7	8	83	51	105	2.9	1.67
8	10	67	13	57	2.2	0.64
9	16	45	5	25	3.4	0.13
10	10	19	4	22	2.6	0.09
	5% lsd=		30	----	0.5	0.37

[1]Scionwood was not available because of tree removal of ortet #4 and #5.

Table 3.—Stem diameter, acorn production after 4 years, and the number of acorns per trunk cross sectional area (TCSA) averaged across eight scion sources when grafted onto half-sib family seedling rootstocks derived from the ortets described in Table 1

Rootstock Family no.	No. of ramets	Percent bearing	Acorns per grafted ramet		Average d.b.h. (cm)	Acorns/TCSA (no./cm^2)
			Average	Maximum		
1	22	83	51	126	2.9	1.66
2	10	100	57	146	3.1	1.78
3	23	92	27	126	2.8	0.98
4	22	75	44	186	3.2	1.32
5	15	62	21	116	2.7	0.73
6	23	85	34	91	2.9	1.23
	5% lsd=		26	-	0.9	0.28

Swamp white oak can be easily propagated by grafting. The use of specific scion genotypes or rootstock families did not increase grafting success rates in this limited study as all graft combinations exceeded 90 percent. Further, we did not observe any evidence of graft incompatibilities (i.e., reduced growth or stunted foliage) among the 48 scion x rootstock combinations. Survival after 3 years for grafts planted into the field exceeded 90 percent. We did not find any significant scion x rootstock interactions, which may be a result of the low numbers of scion x rootstock combinations used in this study (mean = 2.6). Significant scion and rootstock family main effects were detected for both stem diameter and number of acorns produced per grafted tree (Tables 2 and 3).

Acorn productivity was more strongly influenced by the source of the scionwood than rootstock origins based on the probabilities for significant differences. The average number of acorns per grafted tree for the ramets from the precocious (ortet #1 through #7) and non-precocious (ortet #8 through #10) sources closely paralleled cumulative acorn production of the ortets themselves (Tables 1 and 2). Because the grafts had slightly different growth rates, acorn production data were standardized by converting to number of acorns per cm^2 TCSA. It was also found that the ortet rankings for cumulative acorn production during the 4 years from 1999 to 2003 were identical to the scion rankings for the number of acorns produced in 2006 on a TCSA basis except for ortet #1. None of the half-sib progeny from the highly productive swamp white oaks yielded a superior rootstock for grafting (Table 3). Seedlings of ortet #5, when used as a rootstock, tended to exhibit reduced stem diameter and acorn productivity.

CONCLUSIONS

Our study demonstrated that swamp white oak can be readily vegetatively propagated using a whip and tongue graft. Field-planted grafts showed high survival rates with no graft incompatibility evident after four growing seasons when using scion and rootstocks originating from a common maternal source. Unlike half-sib seedlings, the 127 grafts used in this study exhibited similar patterns of precocity and acorn production as the source tree used for scionwood. It is suggested that the number of acorns produced per unit TCSA in young swamp white oak grafts can serve as an indirect measure of ortet acorn productivity when such cumulative seed production figures are unknown. Based on these findings, highly precocious individual swamp white oak trees can be readily identified and potentially utilized as grafted stock for the production of reforestation seedlings that may be capable of flowering and fruiting at a young age, depending upon the heritability of this important trait. In addition, if delayed compatibility does not become a problem in this species, such grafted trees may possibly be planted directly into landscapes where wildlife enhancement is a management objective. While the results derived from the present study hold promise, we suggest more research by utilizing a greater range of swamp white oak origins to determine if such findings can be generalized across the species.

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SINGLE-TREE HARVESTING REDUCES SURVIVAL AND GROWTH OF OAK STUMP SPROUTS IN THE MISSOURI OZARK HIGHLANDS

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Abstract.—Regeneration and recruitment into the overstory is critical to the success of using uneven-aged systems to sustain oak forests. We evaluated survival and growth of white oak (*Quercus alba* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.) stump sprouts 10 years after harvesting Ozark forests by the clearcut, group selection, or single-tree selection method. After 10 years, the percent of stumps with live sprouts was high for all species in clearcuts (75 percent) and group selection openings (ranging from 60 to 78 percent depending on species), but was substantially less in single-tree selection units (ranging from 32 to 50 percent depending on species). Stump sprout 10th-year height and diameter at breast height (d.b.h.) was largest in clearcuts, intermediate in group selection openings, and smallest in single-tree selection units. White oak and black oak growth was not significantly different between clearcut and group openings, but it was significantly less in single-tree selection units. Scarlet oak growth in clearcuts was significantly more than either uneven-aged method, and differences between group and single-tree selection were significant. Single-tree selection harvesting as conducted in this study has lowered survival and growth of oak stump sprouts, and slowed their recruitment into the overstory. Inadequate light levels in the understory are probably limiting oak development. Long-term ability of this regeneration method to sustain oak stocking in these forests needs further study.

INTRODUCTION

Forest managers throughout eastern North America often desire to maintain current levels of oak (*Quercus* spp.) stocking for timber, wildlife, and conservation biology reasons. Even-aged methods such as clearcut and shelterwood harvesting are recommended to regenerate eastern oak species; uneven-aged methods such as single-tree and group selection are not considered appropriate for sustaining oak ecosystems (Roach and Gingrich 1968, Sander and Graney 1993). Oak forests managed by the single-tree selection method typically transition to more mixed mesophytic, shade-tolerant species, with substantially reduced levels of oak stocking (Schlesinger 1976, Della-Bianca and Beck 1985, Smith and Miller 1987). The group selection method promotes the regeneration of more shade-intolerant species such as the oaks, but small openings (< 0.1 acre) are often dominated by shade-tolerant species, and larger openings are captured by fast-growing shade-intolerant species such as yellow-poplar (*Liriodendron tulipifera* L.) and black cherry (*Prunus serotina* Ehrh.) (Smith 1981, Weigel and Parker 1997, Jenkins and Parker 1998). However, concerns from certain environmental groups about forest harvesting have led state and federal agencies to experiment with or adopt uneven-aged systems (single-tree or group selection) for managing eastern oak forests.

In the Missouri Ozark Highlands, however, uneven-aged management has been practiced on the privately owned Pioneer Forest for more than 40 years, and the practice has been used on state and federal land for more than a decade. Johnson and others (2002, p. 358) recognized that "[t]here is substantial evidence that the single-tree selection method can be used to sustain oak stands in the Ozark Highlands." Their evidence is based on analysis of Pioneer Forest continuous forest inventory (Loewenstein 1996, Loewenstein and

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others 2000). However, they do qualify this optimistic report by noting that the long-term sustainability of this method needs to be verified.

Stump sprouts are the most competitive source of oak reproduction (Johnson and others 2002) and an evaluation of their development after uneven-aged harvesting would be indicative of the method's ability to sustain current oak stocking levels. Of particular interest is the effect of a partial overstory and small group openings on oak stump sprout survival and growth. Most studies of oak stump sprouting address how sprouts develop in clearcuts, or openings larger than 0.5 acres (Wendel 1975, Lynch and Bassett 1987, Dey and others 1996). Less is known about the persistence and competitiveness of oak stump sprouts that develop in single-tree gaps and in small (<0.5 acres) group openings. Gardiner and Helmig (1997) studied survival and growth of water oak (*Q. nigra* L.) stump sprouts in young (i.e., ≤30 years old), thinned bottomland plantations in Louisiana. They found that substantial reductions in stand density, i.e., removing 60 percent of basal area, increased survival of oak stump sprouts after 7 years. Lockhart and Chambers (2007) reported that removing half of the overstory basal area did not increase fifth-year survival of cherrybark oak (*Q. pagoda* Raf.) stump sprouts in a Louisiana plantation. However, they suggested that sprout survival was compromised by 2 years of drought. Long and others (2004) reported that survival of upland oak stump sprouts was 93 percent 2 years after reducing basal area by 29 percent by thinning from below in southern Ohio forests.

OBJECTIVES

The purpose of this study was to determine the effect of regeneration method: clearcut, group selection, and single-tree selection on the survival and growth of oak stump sprouts in the Missouri Ozark Highlands. We present a 10-year assessment of sprouting capacity and growth performance in three oak species, white oak (*Q. alba* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.).

METHODS

We monitored stump sprouting of oak trees in stands harvested by the clearcut, group selection, or single-tree selection regeneration method located in Shannon, Carter, and Reynolds Counties, MO. The study stands are located within the Current River oak forest breaks and the Current River oak-pine woodland hills landtype associations (Nigh and Schroeder 2002). Before harvesting, study stands were fully stocked, mature forests dominated by white oak, black oak, scarlet oak, and post oak (*Q. stellata* Wangenh.), which comprised 71 percent of the basal area (Kabrick and others 2004). Shortleaf pine (*Pinus echinata* Mill.) was 8 percent of original basal area. The remaining species included pignut hickory (*Carya glabra* (Mill.) Sweet), black hickory (*C. texana* Buckl.), mockernut hickory (*C. tomentosa* Poir. Nutt.), flowering dogwood (*Cornus florida* L.), and blackgum (*Nyssa sylvatica* Marsh.). Initial stand density averaged about 84 ft^2 per acre, 150 trees per acre, and 84 percent crown cover for trees greater than 4.5 inches d.b.h.

This study was part of the Missouri Forest Ecosystem Project (MOFEP) that was designed as a randomized complete block study (Sheriff and He 1997). Each management treatment (even-aged, uneven-aged, and no harvesting) was randomly assigned to large, approximately 1,000-acre, forest compartments within each of three blocks. Blocks were landscapes large enough to accommodate three 1,000-acre treatments and were subjectively chosen to maximize homogeneity in site and stand conditions within a block. A total of 648 half-acre permanent plots were randomly located across all blocks and management treatment compartments, and were apportioned to each ecological landtype as they occurred within the study area.

Table 1.—Distribution of oak stumps by species and harvest treatment sampled on the Missouri Ozark Forest Ecosystem Project

Species	Clearcut	Group Selection	Single-tree selection	Total
White oak	158	93	131	382
Scarlet oak	65	21	56	142
Black oak	69	49	60	178
Total	292	163	247	702

Single-tree and group selection harvesting was implemented according to the guidelines presented in Law and Lorimer (1989). In single-tree selection units, the target residual basal area was chosen to be B-level stocking, i.e., about 58 percent stocking, according to Gingrich (1967). The target largest diameter was set at 18 inches d.b.h. in stands of low site quality and 26 inches d.b.h. where site quality was high. The target q-value averaged 1.5, but ranged between 1.3 and 1.7 at the stand level depending on the actual distribution of tree diameters. Group openings were 0.1 acre (one tree height in diameter, about 75 feet) on south and west aspects, 0.2 acres on ridges, and 0.4 acres (two tree heights in diameter, about 150 feet) on north and east aspects. The cutting cycle for uneven-aged units was set at 15 years. Ten percent of the stands in each compartment were harvested in the initial treatment, which was completed in the fall of 1996. Immediately following the timber harvest, all unmerchantable stems in clearcuts and group openings were cut by chainsaw in the winter of 1996-1997. In single-tree units, unmerchantable stems in over-stocked diameter classes were cut or double-girdled. Woody vegetation was inventoried after the harvest treatments were applied (Grabner 2000, Jensen 2000). The post-harvest overstory in clearcuts averaged 7 ft^2 per acre, eight trees per acre and 3 percent crown cover. No overstory was left within group selection openings. In contrast, stand density after harvest in single-tree selection units averaged 62 ft^2 per acre, 122 trees per acre, and 58 percent crown cover.

Within the harvested stands, we randomly selected oak stumps in clearcuts (292 trees), group selection openings (163 trees), and single-tree selection units (247 trees). We limited the number of trees selected at any given point to less than five per species to distribute the sample across all MOFEP compartments. Stumps were chosen to represent the range of diameters present and were located far enough from each other so they could be considered independent of one another. A total of 702 stumps were selected (Table 1).

Stumps were identified to species and tagged with a unique number, and the diameter of each stump was measured (initial stump diameter). Stumps were referenced to a permanent marker by azimuth and distance. Stumps averaged 9.3 inches in diameter (range 1.7 inches to 33.3 inches) and 61 years in age (range 38 to 192 years). In the fall of 2006, 10 growing seasons after harvesting, stumps were revisited to measure the height and d.b.h. of the tallest sprout.

For each species, we used analysis of variance (ANOVA) (PROC GLM, SAS Version 9.1, SAS Institute, Inc., Cary, NC) to test for significant differences in the logit of proportion of stumps with at least one live sprout 10 years after harvesting by block and harvest treatment (clearcut, group selection, single-tree selection). Similarly, we used ANOVA to test for significant differences in height and d.b.h. of the dominant sprout at year 10 by block, harvest treatment, initial stump diameter class (class 1: <6 inches; class 2: 6 to <11 inches; class 3: ≥11 inches), and the interaction of harvest treatment, and initial stump

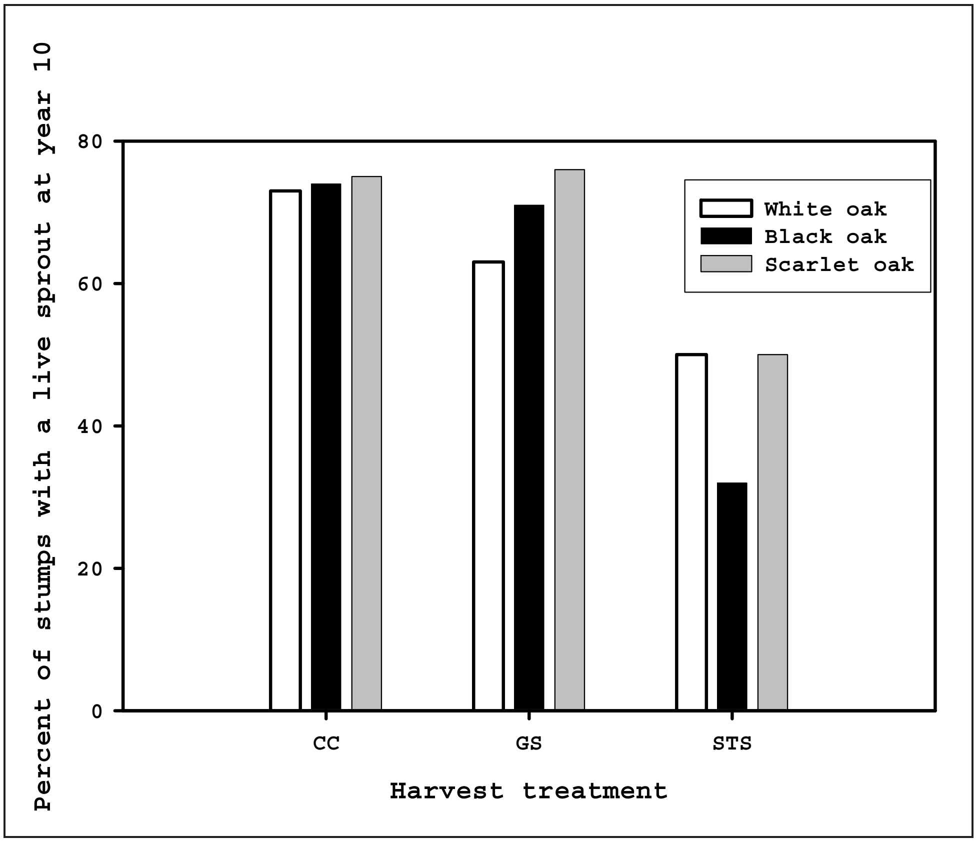

Figure 1.—Percent of stumps that had at least one live sprout 10 years after harvesting by species and harvest treatment (CC = clearcut; GS = group selection; STS = single-tree selection). For each species, differences among harvest treatment are not significantly different ($\alpha = 0.05$).

diameter class for each species. We treated block, harvest treatment and stump diameter class as random effects in all analyses. For significant main effects and interactions ($\alpha = 0.05$), differences between least squares means were determined by pairwise comparisons.

RESULTS

Proportion of Sprouting Stumps

Ten years after harvesting, we found that the percent of stumps with at least one live sprout was high (e.g. 75 percent) in clearcuts and group selection openings for all species, but was only 32 percent (black oak) and 50 percent (white oak and scarlet oak) in single-tree selection treatments (Fig. 1). Despite the absolute differences in average percent of stumps with live sprouts by harvest treatment, there was no evidence that the logit of proportion of stumps with a live sprout was significantly affected by block or harvest treatment within a species at year 10.

Height and Diameter

Ten years after harvesting, we found that the dominant sprout was tallest in clearcuts, intermediate in group openings, and substantially smaller in single-tree units (Table 2). Height differences among the harvest treatments were greatest for black oak and scarlet oak. White oak in clearcuts and group selection openings were similar in height. Among the species, scarlet oak stump sprouts were nominally the tallest, on average, in clearcuts at 10 years. Height of white oak and black oak stump sprouts was statistically

Table 2.—Mean 10th-year height and diameter (d.b.h.) of dominant stump sprout by species and harvest treatment. For a species, mean heights or diameters among harvest treatments with different letters are significantly different at α=0.05.

Regeneration method	Height (feet)	d.b.h. (inches)
White oak		
Clearcut	15.5 a	2.2 a
Group selection	13.6 a	1.5 a
Single-tree selection	5.2 b	0.4 b
Scarlet oak		
Clearcut	25.0 a	3.1 a
Group selection	13.2 b	1.4 b
Single-tree selection	6.5 c	0.7 b
Black oak		
Clearcut	18.6 a	2.3 a
Group selection	12.5 a	1.3 b
Single-tree selection	5.1 b	0.4 c

similar in clearcuts and group selection openings, but significantly reduced in single-tree selection treatments. For scarlet oak, height of stump sprouts in clearcuts was significantly greater than in group and single-tree selection openings; height in group selection openings was significantly greater than in single-tree harvest treatments.

Tenth-year d.b.h. of the dominant stump sprout was greatest in clearcuts for all oak species, intermediate in group openings, and smallest in single-tree treatments (Table 2). Stump sprout d.b.h. averaged about 2.0 inches larger in clearcuts than in single-tree selection treatments. Scarlet oak stump sprouts were the largest, averaging 3.1 inches in clearcuts, almost an inch larger than either white oak or black oak. In general, d.b.h. of the dominant sprout was significantly larger in clearcuts than either of the uneven-aged harvest treatments for all oak species. One exception was white oak, whose d.b.h. was statistically similar in clearcuts and group openings. Black oak and white oak d.b.h. in group selection openings was significantly greater than in single-tree treatments, but there was no statistically detectable difference between scarlet oak d.b.h. in group and single-tree selection treatments.

In general, sprouts from smaller diameter stumps grew taller in height and larger in d.b.h. for all oak species in 10 years (Table 3). Average sprout height was nominally the largest for stumps that were <6 inches in diameter. The average height of the dominant stump sprout was significantly greater for sprouts arising from smaller stumps (<12 inches in diameter for all oak species). For white oak, sprout height was significantly greater for stumps that were < 6 inches compared to sprouts from larger stumps after 10 years. Similarly, sprout d.b.h. was significantly greater for stumps <12 inches in diameter than for sprouts from larger stumps for all oak species. Sprouts from stumps that were <12 inches d.b.h. were usually an inch larger in d.b.h. than sprouts from larger oak stumps after 10 years. There were no significant interactions between harvest treatment and stump diameter class on stump sprout height or d.b.h. for any of the oak species.

Table 3.—Mean 10th-year height and diameter (d.b.h.) of dominant stump sprout by species and stump diameter size class. For a species, mean heights or diameters among stump diameter size classes with different letters are significantly different at α=0.05.

Stump diameter (inches)	Height (feet)	d.b.h. (inches)
White oak		
<6	16.2 a	1.9 a
6 to <11	11.6 b	1.5 a
≥11	6.4 c	0.7 b
Scarlet oak		
<6	19.2 a	2.1 a
6 to <11	16.8 a	2.0 a
≥11	8.6 b	1.1 b
Black oak		
<6	13.9 a	1.6 a
6 to <11	15.6 a	1.7 a
≥11	6.7 b	0.7 b

DISCUSSION

Stumps in this study averaged 9 inches in diameter and 61 years in age, which places them in prime sprouting condition for these oak species (Johnson and others 2002). Gardiner and Helmig (1997) also observed very high initial sprouting (100 percent) in young (28-year-old), small-diameter water oak under a partial overstory created by thinning a bottomland plantation in Louisiana. Lockhart and Chambers (2007) found that 85 to 95 percent of cherrybark oak stumps (average d.b.h. 11 inches) produced sprouts after thinning to either 50 or 75 percent stocking in a 30-year-old Louisiana bottomland plantation. In a mature bottomland oak forest in southeast Missouri, Kabrick and Anderson (2000) reported that stumps of pin oak (*Q. palustris* Muenchh.), cherrybark oak, and willow oak (*Q. phellos* L.) in single-tree gaps sprouted as readily as stumps of upland oaks in clearcuts. Their sprouting frequencies were also comparable to open-grown stump sprouts in this study. McGee (1978) reported no difference in the ability of white oak stumps to produce sprouts when growing in small canopy gaps and forest openings.

We observed that percent of stumps with any live sprouts remained high among species in clearcuts (75 percent on average) and group openings (ranging from 63 to 76 percent) 10 years after harvesting. Oak stump sprouts are vigorous and competitive in these Ozark forests, and are able to survive relatively well when given sufficient growing space and light. The percent of stumps with a live sprout was much lower in single-tree units where the residual overstory averaged 62 ft^2 $acre^{-1}$ and 58 percent crown cover. Under these overstory densities, light levels begin to limit oak reproduction survival and growth (Larsen and others 1997, Dey 2002).

Gardiner and Helmig (1997) found that survival of water oak stump sprouts remained relatively high (80 percent) 7 years after a moderate thinning that reduced plantation basal area by 60 percent, and that this survival was 23 percent higher than that of stump sprouts in plots where only 40 percent of the basal area was removed. No doubt greater reductions in stand density permitted additional light to reach the oak sprouts in the years immediately following thinning, thus improving their survival for up to 7 years. In another bottomland plantation thinning study, Lockhart and Chambers (2007) reported initially very high stump sprouting in cherrybark oak after a heavy (50 to 55 percent reduction in stocking) and light (25 to 30 percent reduction in stocking) thinning. But over the next 5 years, they noticed that stump sprout survival dropped to 30 to 40 percent and there was no difference between thinning treatments. Benefits to stump sprout survival and growth that were expected in the heavy thinning may have been reduced by a 2-year drought.

Height and diameter growth of oak stump sprouts was greatest in clearcuts after 10 years. The reduction in height and diameter as a result of harvest treatment (clearcut < group opening << single-tree selection) was least in white oak, intermediate for black oak, and substantial for scarlet oak, which probably mirrors the difference in shade tolerance among these species (Burns and Honkala 1990). Scarlet oak is one of the most shade-intolerant oak species found in the Missouri Ozark Highlands. Lockhart and Chambers (2007) noted that height growth of cherrybark stump sprouts growing under partial overstory shade were consistently higher with lower residual stand densities for 5 years after thinning, but differences were insignificant primarily because of a 2-year drought that occurred following thinning. Gardiner and Helmig (1997) reported that height and diameter growth of water oak stump sprouts were significantly greater for 5 years after thinning under the lower stand density treatment, but by year 7 and with canopy closure, stump sprout heights were statistically similar among the thinning treatments.

Managers have been discouraged from using uneven-aged systems in oak forests largely because of oak's inability to survive and grow in moderate to high levels of shade under high residual forest overstory densities, or because oak do not compete well with fast growing shade-intolerant species, such as yellow-poplar and black cherry in larger group selection openings.

It is commonly reported that light levels in forest understories and regeneration openings should be between 30 and 50 percent of full sunlight to promote development of oak reproduction (Hanson and others 1987, Hodges and Gardiner 1993, Ashton and Berlyn 1994, Gottschalk 1994). Shelterwood harvesting should leave a residual stocking of ≤60 percent, and the diameter of group selection openings should be a minimum of one to two times the height of the adjacent dominant trees to produce 30 percent or more of full sunlight in the regeneration environment (Minckler and others 1973, Sander 1979, Dey and Parker 1996).

In this study, group openings, which varied in size from one tree height in diameter on south-west aspects to two tree heights on north-east aspects, initially provided the one-third or more of full sunlight recommended for good oak growth according to the literature. Position of oak reproduction in the group opening is important for survival and growth. Trees growing in the center of group openings grow at rates similar to trees in clearcuts, but oaks along the edges of openings are inhibited by the shade from the adjacent stand. Our survival and growth results for oak stump sprouts in group openings are averages of the sample trees regardless of their location in the group. In the single-tree selection units it is doubtful that oak stump sprouts received more than one-third of full sunlight, probably less in many cases given the residual stand basal area. Single-tree selection harvest in mature, closed-canopied hardwood forests may not appreciably increase light levels at the forest floor (Fischer 1979).

Overstory density was important for developing large oak advance reproduction in Missouri Ozark (Larsen and others 1997) and Lower Michigan (Johnson 1992) xeric oak ecosystems, where the probability of having large oak reproduction was greatest at stocking levels between 30 and 60 percent (Gingrich 1967). Larsen and others (1999) recommended maintaining overstory density at less than 63 ft^2 $acre^{-1}$ on average over a 20-year cutting cycle to favor oak recruitment in forests managed to produce an uneven-aged structure in the Missouri Ozarks. The overstory in our single-tree selection stands, which was at the upper limit of residual overstory density recommended by Larsen and others (1999), did reduce the height of the tallest stump sprout. The long-term survival and recruitment success of these sprouts remains unknown.

In the xeric oak forests of the Missouri Ozark Highlands, there is hope that uneven-aged systems can be devised to sustain these oak dominated ecosystems. In the case of Pioneer Forest, implementation of the regeneration method has changed over time, and residual stand densities have increased from about 30 to 60 ft^2 $acre^{-1}$, making it difficult to draw conclusions about the sustainability of the system (Loewenstein 1996, Loewenstein and others 2000). More monitoring is needed on public lands managed under uneven-aged systems to determine the future of these forests. In addition, it has been noted elsewhere that there are subtle shifts in species dominance in Ozark forests harvested by uneven-aged methods, with white oak increasing in importance, black oak and scarlet oak decreasing because of problems with regeneration, and loss of shortleaf pine following complete failure to regenerate under moderate to high residual stocking (e.g., 60 ft^2 $acre^{-1}$) in single-tree selection harvested stands, or in small canopy gap openings (Stambaugh 2001, Sasseen 2003, Kabrick and others 2007).

Harvest method and, in particular, management of overstory density are important in determining oak regeneration and recruitment success, i.e., long-term survival and growth of oak stump sprouts and advance reproduction into maturity as codominant and dominant trees. Recruitment into the overstory of oak stump sprout and large oak advance reproduction is critical to success of uneven-aged management of oak forests in the Missouri Ozarks. We have seen by this study that, as implemented in the MOFEP, single-tree selection harvesting greatly reduces the overstory recruitment potential of oak stump sprouts. Timing of future harvest entries will be crucial to promoting development of oak stump sprouts and other reproduction and continuing their recruitment into the overstory. These results may suggest modifications be made to target tree d.b.h., q-values, and target residual stand basal area to provide more light to oak reproduction in the understory. The length of the cutting cycle may need to be rethought because it can be crucial in stopping the decline in oak stump sprout development, which is also indicative of what is happening to oak advance reproduction. Oak reproduction can be released earlier by shortening the cutting cycle, but this approach must be balanced with other concerns, stand growth and yield, and the economics of harvesting.

There is flexibility in how the many even-aged and uneven-aged systems are applied to sustain oak forests in the Missouri Ozark Highlands. How these methods are implemented is critical to meeting the variety and complexity of management goals. Further monitoring of sprouts in this study will provide valuable insight on how we should manage regeneration and recruitment processes. Managers can use these results to help determine when uneven-aged management is appropriate and to develop detailed stand prescriptions that consider the full range of silvicultural systems.

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COMPARING SINGLE-TREE SELECTION, GROUP SELECTION, AND CLEARCUTTING FOR REGENERATING OAKS AND PINES IN THE MISSOURI OZARKS

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Abstract.—In the Missouri Ozarks, there is considerable concern about the effectiveness of the uneven-aged methods of single-tree selection and group selection for oak (*Quercus* L.) and shortleaf pine (*Pinus echinata* Mill.) regeneration. We compared the changes in reproduction density of oaks and pine following harvesting by single-tree selection, group selection, and clearcutting during a 10-year period in the Missouri Ozarks. Inventories in permanent plots were completed preharvest (1995) and post-harvest (1998, 2002, and 2006). Prior to harvesting, advance oak regeneration densities (trees < 4.5 inches diameter at breast height [d.b.h.]) ranged from 144 to 173 trees per acre. Ten years after harvesting, oak density in clearcut stands increased to 1,049 trees per acre and was about two times greater than in group openings (514 trees per acre) and more than four times greater than where single-tree selection (236 trees per acre) was used. Pine (trees < 4.5 inches d.b.h.) averaged nine trees per acre prior to harvesting and decreased to eight trees per acre in clearcut stands. In stands harvested with group selection or single-tree selection, pine remained at about two to three trees per acre on average, but most stands had none. These findings suggest that both group and single-tree selection do regenerate oaks but not as well as clearcutting. None of these methods as currently practiced are regenerating pine.

INTRODUCTION

In the Ozarks Highlands even-aged regeneration methods such as clearcutting and shelterwood harvesting have proven to regenerate oaks successfully (Johnson and others 2002). However, forest managers in this region are increasingly interested in applying uneven-aged methods such as single-tree and group selection to oak stands for aesthetic reasons and for the habitat created by maintaining complex and nearly-closed forest canopies at both stand and landscape scales.

At one time, oak-dominated stands were considered unsuitable for uneven-aged silviculture (Roach and Gingrich 1968, Sander and Clark 1971). There is now evidence, however, that uneven-aged methods can sustain and recruit oaks in some stands in the Ozark Highlands (Larsen and others 1999, Loewenstein and others 2000). Still, it is not clear how successfully uneven-aged methods will work when applied in mature stands that are currently even-aged (Loewenstein and Guldin 2004). Moreover, few studies have experimentally compared the effectiveness of single-tree or group selection for regenerating oaks to clearcutting, the even-aged method most commonly used in the Missouri Ozarks. Managers were also interested in increasing the abundance of shortleaf pine, which was historically much more prevalent than in recent times.

OBJECTIVES

In 1989, the Missouri Ozark Forest Ecosystem Project (MOFEP) was initiated by the Missouri Department of Conservation (MCD) to compare the effects of even-aged, uneven-aged, and no-harvest

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Table 1.—Basal area and number of trees per acre in the dominant and co-dominant crown classes before and after 1996 harvests using clearcut (twenty 0.5-acre plots), uneven-age selection (122 plots) and nonharvested (380 plots) stands located on ridges, southwest and northeast slopes on MOFEP sites

1995	Basal area (ft per acre)	Standard deviation	Range	Trees per acre	Standard deviation	Range
clearcut	69	9	53-84	71	15	50-98
uneven-age	72	13	42-100	89	26	38-160
no harvest	70	13	27-125	82	28	30-200
1998						
clearcut	6	7	0-22	7	7	0-40
uneven-age	53	15	14-85	71	15	24-150
no harvest	71	13	32-122	81	13	28-192

management of the flora and fauna of Ozark forests (Brookshire and Shifley 1997, Shifley and Kabrick 2002). This project afforded an opportunity to experimentally compare even-aged and uneven-aged methods for regenerating oaks and shortleaf pine.

METHODS

Study Area

The MOFEP study sites consist of nine compartments or sites ranging in size from 776 to 1,275 acres and are located mostly within the Current River Oak Forest Breaks and the Current River oak-pine woodland hills landtype associations of the Ozark Highlands section (37°00´- 37°12´N and 91°01´- 91°31´W) (Kabrick and others 2000). The compartments are located in the Current River and Peck Ranch Conservation Areas in Carter, Reynolds and Shannon counties in Southeast Missouri and are administered by the MDC. Before the start of the study, the compartments had received no management for the prior 40 years. In the study region, the annual temperature is 56 ˚F and the mean annual precipitation is 45 inches, with the majority of rain falling in the spring and fall. The study compartments occur at 560 to 1,180 feet elevation with slopes of 0 to 60 percent and dominant soil parent materials being hillslope sediments, loess, and residuum (Meinert and others 1997, Kabrick and others 2000). Preharvest inventories showed that oaks were the dominant trees and four oak species, white oak (*Quercus alba* L.), black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Muenchh.), and post oak (*Q. stellata* Wangenh.) comprise 71 percent of the basal area. Other oaks found at MOFEP include chinkapin oak (*Q. muehlenbergii* Engelm.), blackjack oak (*Q. marilandica* Muench.), Shumard oak (*Q. shumardii* Buckl.), and northern red oak (*Q. rubra* L.), but in combination they comprise only 1 percent of the basal area. Shortleaf pine (*Pinus echinata* Mill.) (8 percent), pignut hickory [*Carya glabra* (Mill.) Sweet] (4 percent), black hickory (*C. texana* Buckl.) (4 percent), mockernut hickory (*C. tomentosa* Poir. Nutt.) (4 percent), flowering dogwood (*Cornus florida* L.) (3 percent), and blackgum (*Nyssa sylvatica* Marsh.) (2 percent) also are in the study area. Before harvest, trees in the dominant and co-dominant crown classes contributed from 69 to 72 square feet per acre basal area and 71 to 89 trees per acre (Table 1). Prior to the study, compartments were subdivided into stands averaging 12 acres in size with similar forest vegetation composition and age, and environmental characteristics (Brookshire and others 1997). Further descriptions of the MOFEP study can be found in Shifley and Brookshire (2000) and Shifley and Kabrick (2002).

Study Design and Harvest

The study sites were divided into three complete statistical blocks of three compartments each, which were in close proximity to one another. Three compartments within each block were randomly assigned one of three treatments: (1) even-aged management with harvesting by clearcutting and intermediate thinning; (2) uneven-aged management with harvesting using a combination of single-tree selection and group selection; and (3) no-harvest management. The management system was applied at the compartment level and management was implemented at the stand level. The MDC Forest Land Management Guidelines (Missouri Dept. of Conserv. 1986) and the guidelines for managing uneven-age stands (Law and Lorimer 1989) provided general recommendations for harvesting in even-age and uneven-age compartments at MOFEP. The MOFEP study design is described in detail by Sheriff and He (1997), and Sheriff (2002).

The even-aged management treatment uses clearcutting with reserves as the principal means of stand regeneration (Brookshire and others 1997). With this method approximately 10 percent of the area in a forest compartment was initially designated as "old growth" and excluded from future harvesting. During each harvest entry, stands covering about 10 to 15 percent of the remaining area in the compartment are clearcut, with a few trees left unharvested as reserves. Rotation lengths for even-aged compartments are approximately 100 years with a 15-year entry. Reserve trees are retained to provide food and cover for wildlife or, in the case of shortleaf pine, to provide seed for natural regeneration. Reserve trees usually number fewer than 4 to 8 per acre and are generally >12 inches d.b.h. Intermediate thinnings are conducted periodically within stands to improve quality and increase growing space for residual trees. The stands chosen for intermediate thinning usually have some mature and over-mature large sawtimber but also an abundance of quality poles and small sawtimber.

Uneven-aged treatment follows the guidelines developed by Law and Lorimer (1989) and includes a combination of group selection and single-tree selection on a 15-year cutting cycle for timber harvest and forest regeneration. As with even-aged management, approximately 10 percent of the forest compartment was initially designated as "old growth". The remaining area was grouped into stands of 8 to 32 ha. Within stands, group selection methods were used to create openings to regenerate shade-intolerant species. These group openings were approximately one to two tree heights in diameter, depending on aspect. At MOFEP, the group openings are 70 feet diameter (0.1 acre) on southwest-facing slopes, 105 feet (0.2 acre) on ridge tops, and 140 feet (0.35 acre) on northeast-facing slopes. The locations of the group openings were determined by forest managers based on where they would improve the stand quality the most. The total land area of openings was about 5 percent of the total harvested area. Elsewhere in the stand, single-tree selection was used with harvest objectives set by the desired residual basal area, the largest tree diameter to be left in the stand, and the q-value or change across consecutive diameter classes. At MOFEP, the target residual basal area was equivalent to B-level stocking (about 58 percent) with adjustments made for logging damage (Roach and Gingrich 1968). The target largest diameter was about 18 inches d.b.h. in stands of low site quality to 26 inches d.b.h. in stands of high site quality. The target q-value averages 1.5 but can range from 1.3 to 1.7. For all harvesting, re-entries coincide with those of even-aged treatments.

The no-harvest management treatment was not harvested but wildfires are suppressed. Natural events such as tornadoes, fires, and insect and disease outbreaks are treated the same as on any other forest land owned by the MDC, except that salvage harvests will not occur. This treatment serves as an experimental "control" to compare with the two other management practices.

The first MOFEP harvest was conducted from May through October 1996, with slashing being completed in May 1997. On even-aged compartments, 11 percent of the area (320 acres) was clearcut and 15 percent (411 acres) was thinned. On uneven-aged compartments, 57 percent of the area (2,124 acres) was harvested with single-tree selection and group methods. The three even-aged compartments produced 2.5 million board feet and three uneven-aged compartments yielded 3.4 million board feet (Kabrick and others 2002).

Data Collection

Woody vegetation was initially sampled in 1991 and has been re-inventoried approximately every 3 to 4 years since. Woody vegetation was sampled during the dormant season in 648 permanent, 0.5-acre plots distributed approximately equally among the nine compartments (Jensen 2000). At least one plot was established in each stand on all compartments. Live and dead trees ≥4.5 inches d.b.h. were inventoried on the 0.5 acre circular plots; trees between 1.5 and 4.5 inches d.b.h. were inventoried in four, 0.05-acre circular subplots; trees at least 3.3 feet tall and less than 1.5 inches d.b.h. were inventoried in four, 0.01-acre circular subplots nested within the 0.05-acre subplots. Characteristics recorded for each tree were species, d.b.h., status (i.e., live, dead, den, cut, blown-down), and crown class (i.e., dominant, co-dominant, intermediate, suppressed). Plot and subplot data were combined to obtain plot averages by d.b.h. and all values were converted to an acre basis.

Data Analysis

To evaluate the effects of the regeneration methods, we compared the oak reproduction density in 1995, prior to the first harvest entry, to the post-harvest densities determined from three consecutive inventories completed in 1998, 2002, and 2006. The landscape-scale nature of the MOFEP project also allowed us to examine the response to harvesting on different slope positions and aspects (hereafter slope-aspect). MOFEP is a designed, replicated complete block experiment. We conducted a randomized complete block analysis of split plots in space (i.e., slope-aspect classes within compartments) and time (i.e., repeated measures) as outlined by Steel and others (1997). Our primary interest was to examine the interaction between regeneration method and time and the interactions among regeneration method, slope-aspect, and time since harvest. To do this, we used PROC MIXED (SAS version 9.1, SAS Institute, Cary, NC). The four regeneration methods compared were (1) clearcutting; (2) single-tree selection; (3) group selection; and (4) no-harvest. Random effects in our analysis were block (i.e., the three MOFEP statistical blocks), block x treatment, block within treatment and slope-aspect, block x year, and block x treatment x year. Our analysis looked at stands within the three most common slope-aspect classes on moderately-deep or deep soils that were clearcut (24 stands) in the three even-aged compartments, harvested with single-tree selection (98 stands) or group selection (17 stands) in the three uneven-aged compartments, and the nonharvested stands (518 stands) within all nine compartments. Data were averaged at the plot (and stand) and statistical block level prior to analysis. Because the uneven-aged treatment included group openings surrounded by areas harvested with single-tree selection, some plots included subplots with group openings and single-tree selection. In these cases, we allocated data from the subplots into their respective harvest method (i.e., group opening, or single-tree selection). This situation did not occur with the even-aged treatment as all plots in clearcuts or nonharvested plots were in separate stands. For significant interactions ($\alpha = 0.05$), differences between individual (least square) means were determined using Fisher's least significant difference. Data were analyzed in size classes of 3.3 feet height to 1.5 inches d.b.h. and from 1.5 inches d.b.h. to 4.5 inches d.b.h. Grouping these two size classes did not change the results from the analyses conducted separately on these two size classes.

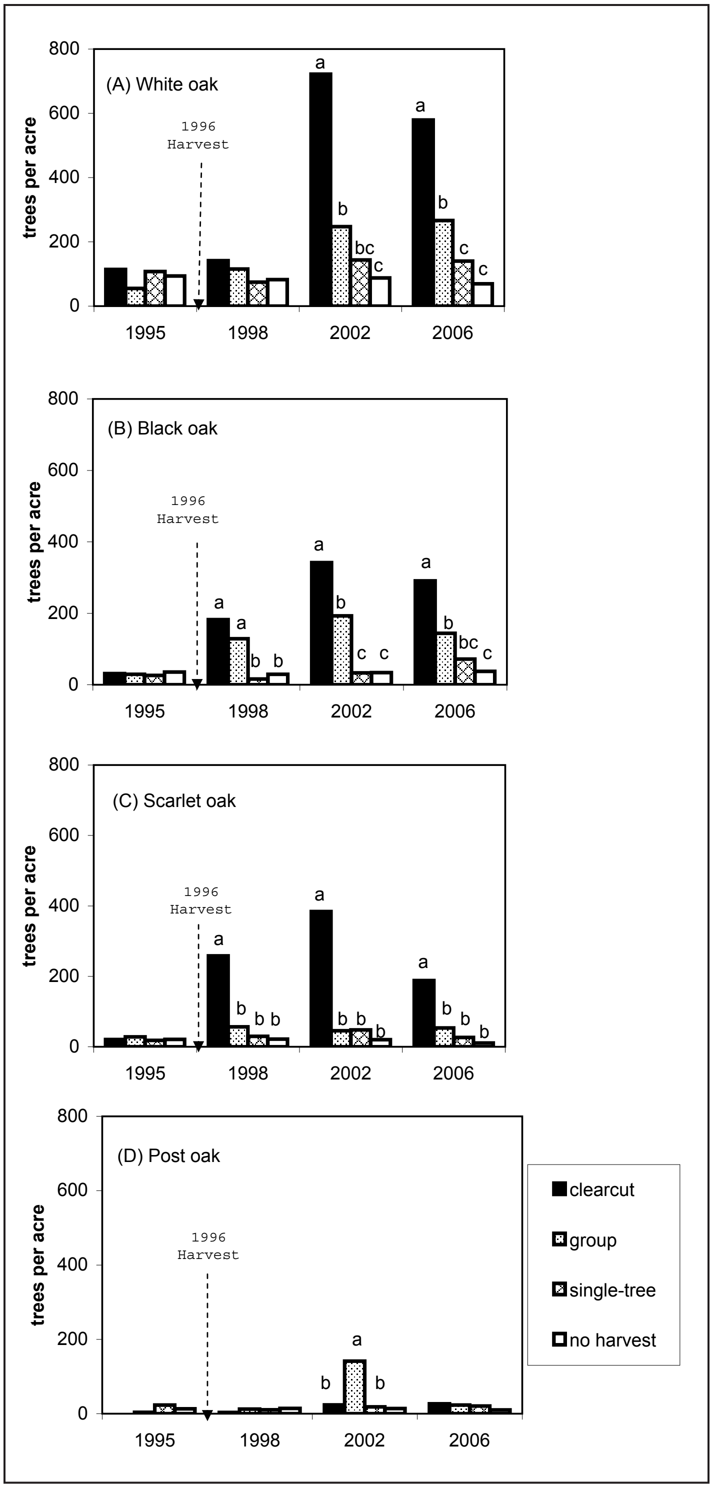

Figure 1.—White oak (A), black oak (B), scarlet oak (C), and post oak (D) regeneration densities of trees <4.5 in. d.b.h. before and after harvesting in 1996. Regeneration methods were clearcutting, group selection and single-tree selection compared to no-harvest management. For a given year, bars with the same letter(s) are not significantly different (α=0.05).

RESULTS

Response to Harvesting

Following the harvest, the basal area of dominant and co-dominant trees ranged from 6 square feet per acre on clearcuts to 71 square feet per acre on nonharvested stands, and seven trees per acre to 81 trees per acre, respectively (Table 1). The preharvest density of oaks (at least 3.3 feet tall and <4.5 inch d.b.h.) ranged from 144 to 173 trees per acre and oaks were 12 to 18 percent of all trees in that size class. White oaks (96 per acre) were the most abundant oak followed by black oak (28 per acre), scarlet oak (21 per acre) and post oak (9 per acre). Small shortleaf pine (<4.5 inch d.b.h.) were not abundant on any treatment preharvest and ranged from one to nine trees per acre.

The density of white oak remained similar to preharvest levels during the first two post-harvest years and then increased markedly in clearcuts (Fig. 1). By 2002, white oaks in clearcut stands exceeded 722 trees per acre compared to 247 per acre in group openings, 144 per acre in stands harvested with single-tree selection, and 88 per acre in nonharvested stands. By 2006, there was a 79 percent reduction in the number of white oaks in clearcuts (579 per acre) compared to 2002. These reductions were caused by competition-induced mortality as the trees entered the stem exclusion stage taking place in clearcut stands. In the same year, the density of white oaks in group openings had increased to 266 per acre, but remained constant in stands harvested with single-tree (140 trees per acre) and nonharvested stands (70 trees per acre).

Following harvesting, black oak densities increased gradually in clearcuts and in group openings and by 2002, there were more black oaks in clearcuts (342 per acre) than in group openings (193 per acre). By 2006, the black oak density in clearcuts remained higher than in group openings, but the density in stands harvested with single-tree selection had increased and was no longer different from group openings. Scarlet oak densities increased only in clearcuts (384 in 2002) and the densities in the other harvest treatments did not differ from each other during the study period. For both black oaks and scarlet oaks, we also observed the same competition-induced mortality in clearcut stands by 2006 as with white oaks.

Post oaks had low densities prior to harvesting and the densities remained low throughout the study period. In 2002, there were more post oak in group openings (142 per acre) than in clearcuts (24 per acre), stands harvested with single-tree selection (18 per acre), and nonharvested stands (14 per acre). This short-lived increase in post oaks resulted from the ingrowth of stems originally < 3.3 tall in two single group openings. These stems subsequently succumbed to competition-induced mortality prior to the final inventory in 2006.

Shortleaf pine was not analyzed statistically because it was absent from most of the plots, but we observed a few notable trends. For example, the density of shortleaf pine decreased after harvesting. By 2006 (year 10) shortleaf pine density decreased from nine to eight trees per acre in clearcut stands and from nine to seven trees per acre in no-harvest stands, but remained the same in stands harvested with single-tree selection (four trees per acre). The only exception to this trend occurred in group openings, where the shortleaf pine density increased from one tree per acre in 1995 to 34 trees per acre in 2006. However, this increase was due to the ingrowth of shortleaf seedlings in only one of the 20 plots sampled.

Response to Harvest by Slope-Aspect

White oak densities (<4.5 inch d.b.h.) were similar on ridges, northeast slopes, and southwest slopes in 1995 and 1998 (Fig. 2). By 2002, however, there were higher densities of white oaks on southwest slopes (1,022 per acre) than on ridges (780 per acre) and northeast slopes (364 per acres). In 2006, there was a slight reduction in white oaks on all slope positions, but densities were still higher on southwest slopes (938 per acre) than on ridges (450 per acre) and northeast slopes (349 per acre).

In group openings, preharvest densities of white oak ranged from 40 trees per acre on northeast slopes to 70 per acre on ridges. Densities in 1998 were similar. In 2002, there were more white oaks in openings on ridgetops (390 per acre) than on northeast (227 per acre) or southwest slopes (125 per acre). By 2006, white oak densities had increased on northeast slopes to 383 trees per acre, which was not significantly different from ridges (273 per acre), but was significantly higher than on southwest slopes (142 per acre). White oak densities were not different among slope-aspects in single-tree selection and nonharvested stands and they stayed at near preharvest densities through the years.

In 1995, black oak densities in clearcuts ranged from 8 trees per acre on ridges to 68 per acre on southwest slopes. In 1998, ridges had more black oak (418 per acre) than did southwest slopes (70 per acre) and northeast slopes (59 per acre; Fig. 3). In 2002, black oak densities increased to 468 trees per acre on ridges, but southwest slopes (340 per acre) now had similar densities. By 2006, southwest slopes (383 per acre) and ridges (308 per acre) had similar densities of black oak and more than northeast slopes (181 per acre).

Black oak densities in group openings followed a different trend than in clearcuts (Fig. 3). In 2002, there were more black oak on southwest slopes (298 per acre) and northeast slopes (228 per acre) than on ridges (53 per acre). This trend was similar in 2006 (256, 157, and 20 trees per acre, respectively). There were no differences between black oak densities among years for the three slope-aspect classes in single-tree selection and nonharvested stands.

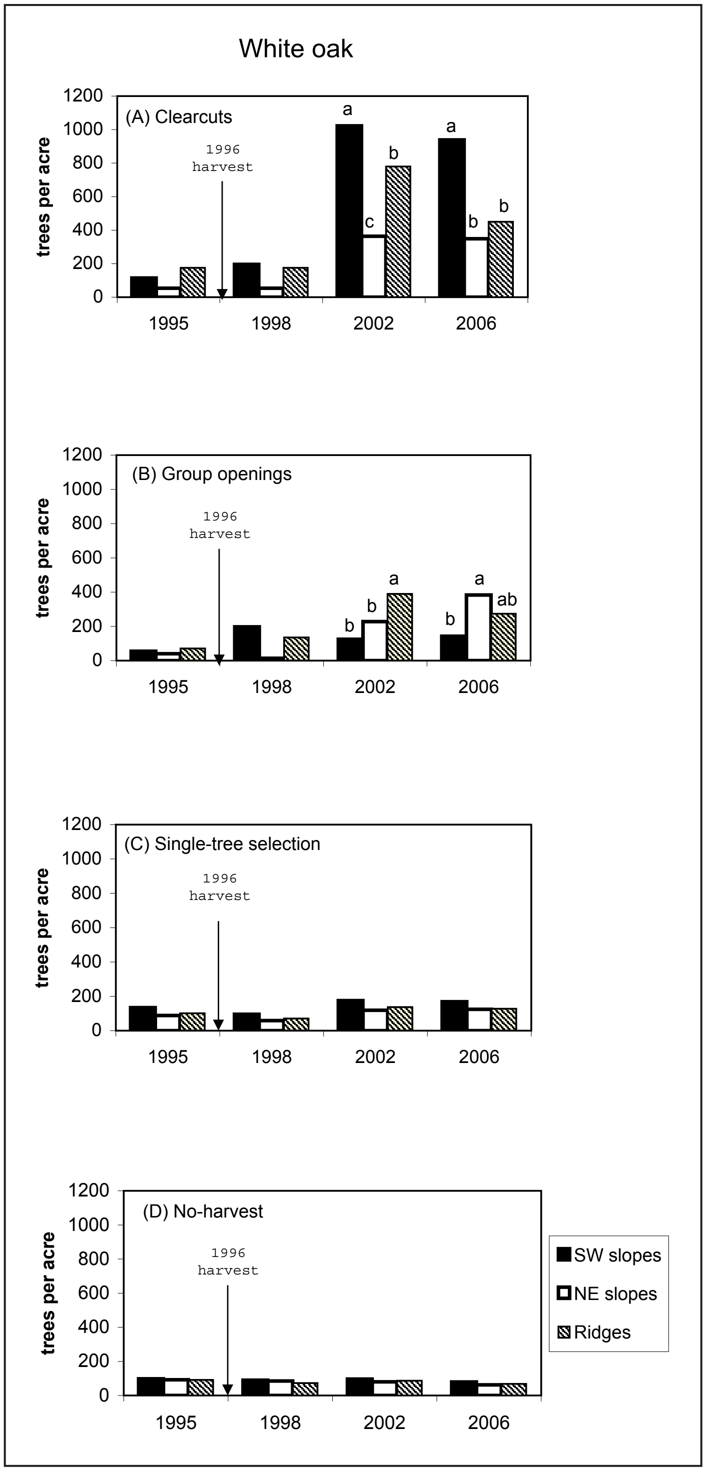

Figure 2.—White oak regeneration density of trees <4.5 in. d.b.h. by slope-aspect class before and after harvesting in 1996 by (A) clearcutting, (B) group selection, (C) single-tree selection, or (D) no-harvest management. For a given year, bars with the same letter(s) are not significantly different (α=0.05).

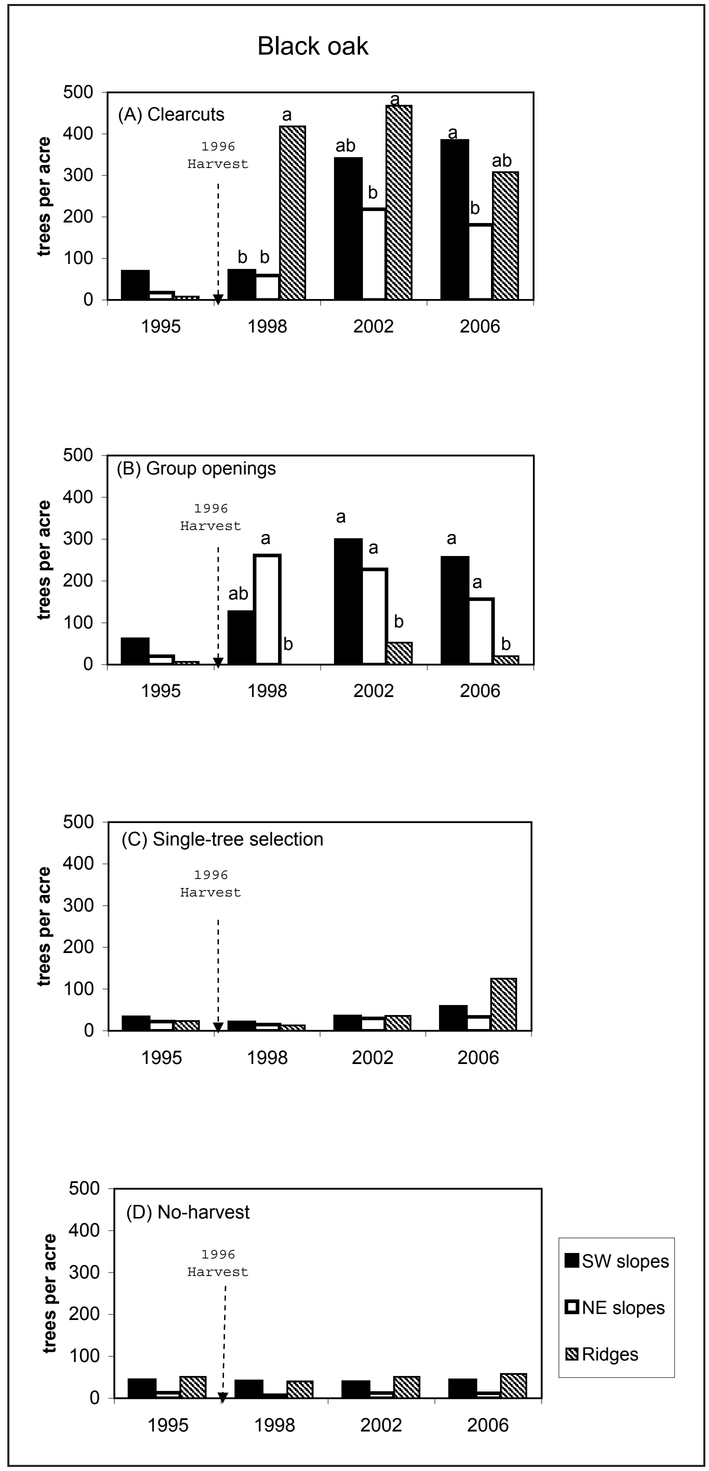

Figure 3.—Black oak regeneration density of trees <4.5 in. d.b.h.) by slope-aspect class before and after harvesting in 1996 by (A) clearcutting, (B) group selection, (C) single-tree selection, or (D) no-harvest management. For a given year, bars with the same letter(s) are not significantly different (α=0.05).

In 1998, scarlet oak densities in clearcuts were significantly higher on ridgetops (620 per acre) than southwest slopes (116 per acre); both had significantly higher densities than northeast slopes (38 per acre, Fig. 4). This trend was the same in 2002, with scarlet oak densities at 634, 341, and 178 trees per acre, respectively. Although scarlet oaks were at reduced densities on ridgetops (312 per acre) in 2006, they were still more abundant than on northeast slopes (147 per acre) or southwest slopes (105 per acre).

Ten years after group opening harvests, there were more scarlet oak on northeast slopes (107 per acre) and ridgetops (45 per acre) than on southwest slopes (10 per acre). There were no differences in scarlet oak densities on any slope-aspects in any of the years with single-tree selection harvests or in nonharvested stands.

The only difference detected in post oak densities among slope-aspect classes occurred in group openings in 2002 (Fig. 5). Post oak densities were estimated at 251 trees per acre on southwest slopes, which was similar to ridgetops (167 per acre) and significantly higher than on northeast slopes (7 per acre). This result, however, reflects large increases of post oak densities in only two plots.

DISCUSSION

White oak, black oak, and scarlet oak increased substantially in density with increasing harvest intensity (Fig. 1). The highest densities were found in clearcuts followed by group openings, single-tree selection harvests and nonharvested stands. By 1998, density increases had not yet materialized for most oak species because the majority of stems had not reached the minimum size threshold of 3.3 feet height by that time. In clearcuts, the tallest sprouts of sprouting stumps of white oak averaged 3.6 feet, scarlet oak 4.5 feet, and black oak 4.3 feet one growing season after harvest (Dey and Jensen 2002). In 1998, clearcuts had an average of 700 stump sprouts per acre, but plots harvested by a combination of single-tree selection and group openings had fewer than 120 stump sprouts per acre. There was an average of 42 stump sprouts per acre on plots harvested by single-tree selection and 7 sprouts per acre on nonharvested plots. Seedling sprouts and advance reproduction contributed to the rest of the regeneration (Kabrick and others 2002). Two years after harvest, clearcuts did have higher densities of scarlet oak than the other harvest types and had more black oak than single-tree selection and nonharvested stands. The highest densities of all of the four oak species occurred in 2002 and differences among harvest methods became apparent. Lower oak densities in 2006 were mostly due to the onset of stem exclusion due to competition, particularly in clearcuts and group openings.

The response of white oak, black oak, and scarlet oak to harvesting differed by slope position and aspect and these species attained highest densities in clearcuts located on southwest-facing slopes or on ridges. These findings clearly demonstrate that there is an interaction between harvest intensity and slope-aspect in the regeneration of oaks of different species. White oak densities in clearcuts were the highest after 10 years on southwest slopes but reached the highest densities in group openings on northeast slopes and ridgetops. Black oaks reached the highest densities on southwest slopes in clearcuts and group openings, but these densities were not statistically different from densities on ridges using clearcuts or densities on northeast slopes using group openings. Scarlet oak densities were highest on southwest slopes in clearcuts and group openings; however, densities in group openings were not different between southwest and northeast slopes.

Although the regeneration of shortleaf pine is an important issue for forest managers in the Missouri Ozarks, none of the forest harvesting methods applied in 1996 increased pine densities. We suspect that

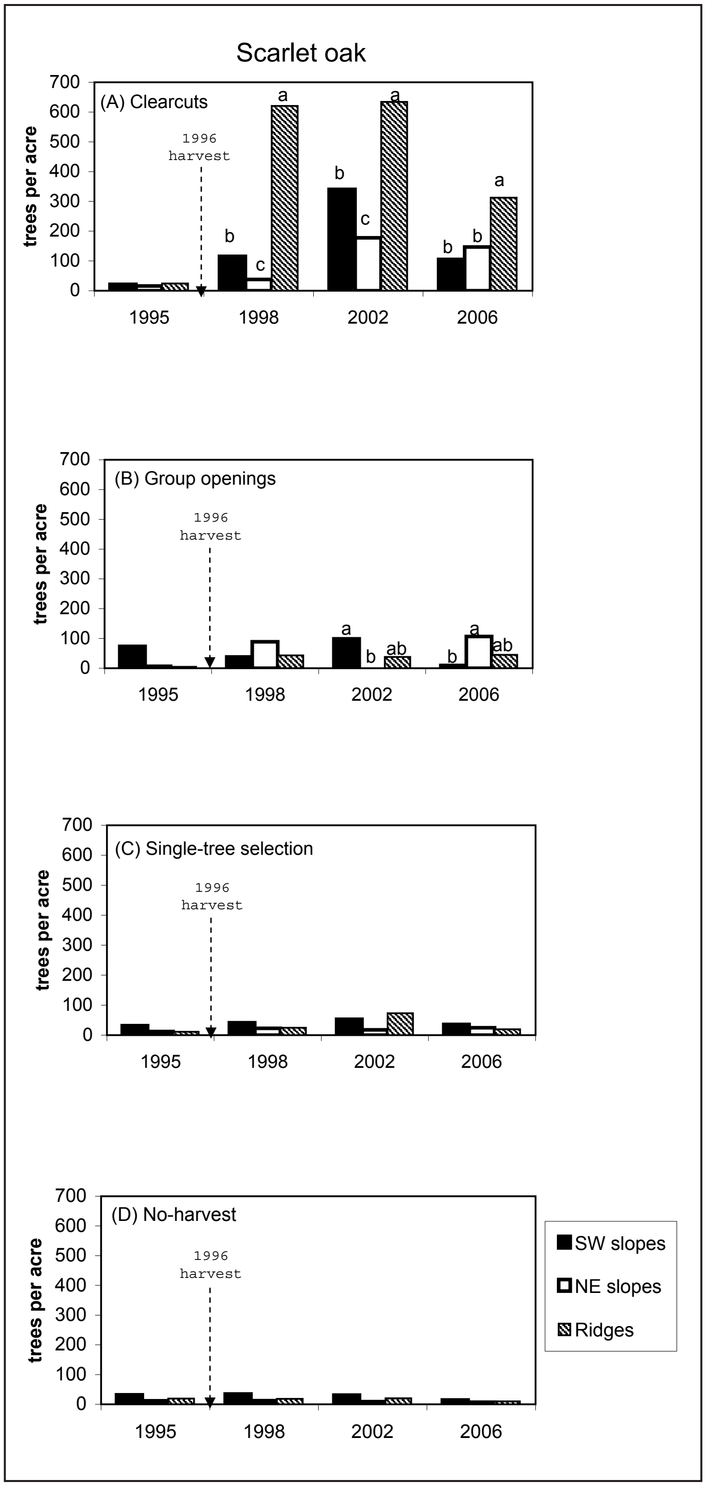

Figure 4.—Scarlet oak regeneration density of trees <4.5 in. d.b.h. by slope-aspect class before and after harvesting in 1996 by (A) clearcutting, (B) group selection, (C) single-tree selection, or (D) no-harvest management. For a given year, bars with the same letter(s) are not significantly different (α=0.05).

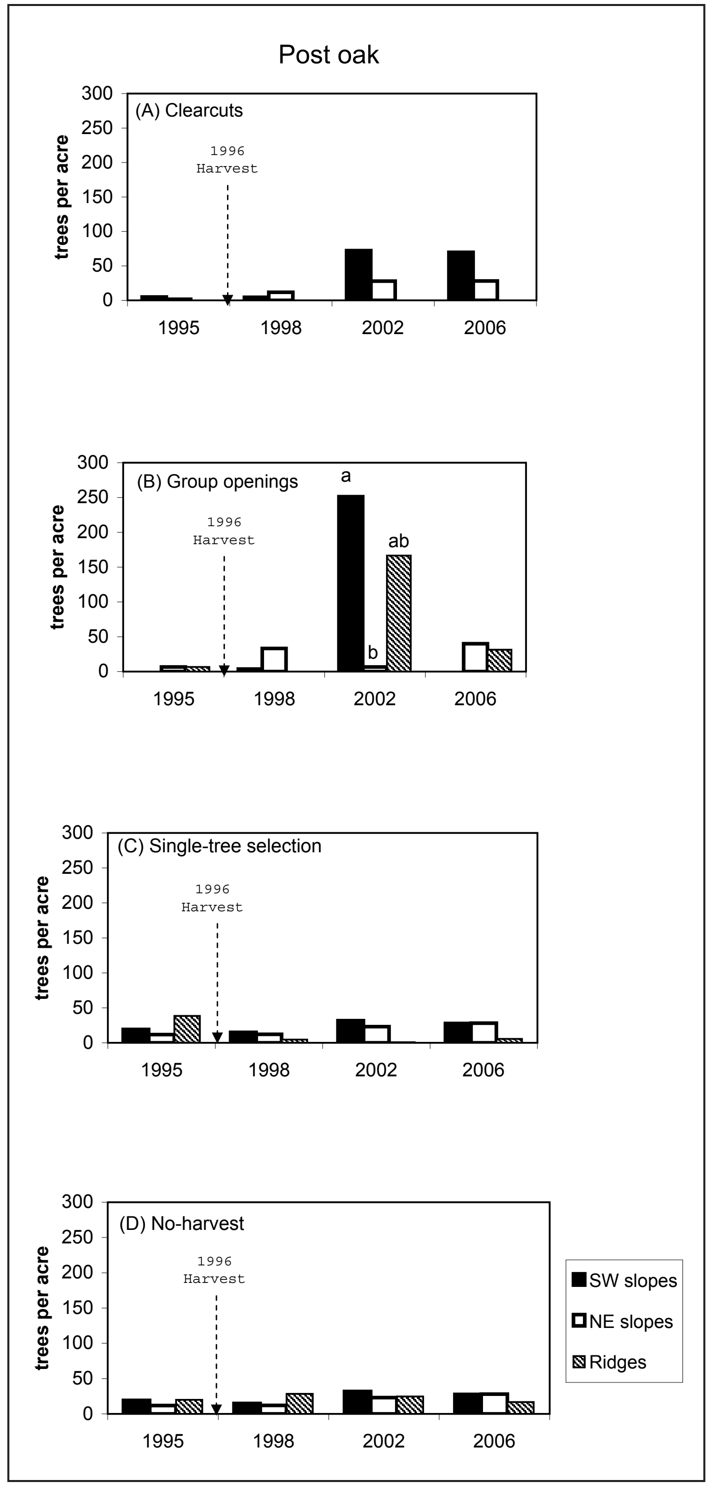

Figure 5.—Post oak regeneration density of trees <4.5 in. d.b.h. by slope-aspect class before and after harvesting in 1996 by (A) clearcutting, (B) group selection, (C) single-tree selection, or (D) no-harvest management. For a given year, bars with the same letter(s) are not significantly different (α=0.05).

the low light levels created by the high density of hardwood seedlings and seedling sprouts in clearcuts and group openings eliminated the shortleaf reproduction. Conversely, the canopy coverage may not have been reduced sufficiently in single-tree selection harvests to benefit the seeding of pine. The lack of scarification of the soil also may have made pine establishment more difficult. Other methods of site preparation and competition control will most likely be needed to increase pine densities.

ACKNOWLEDGMENTS

We thank the many MOFEP field technicians who helped collect the data for this project and Dr. Mark Ellersieck of the University of Missouri for assistance with the analyses. Funding for this study was provided by the Missouri Department of Conservation and the U.S. Forest Service, Northern Research Station.

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RESPONSE OF NORTHERN RED OAK, BLACK WALNUT, AND WHITE ASH SEEDLINGS TO VARIOUS LEVELS OF SIMULATED SUMMER DEER BROWSING

Robert C. Morrissey, Douglass F. Jacobs, and John R. Seifert[1]

Abstract.—Understanding the response of tree seedlings to browsing by white-tailed deer (*Odocoileus virginianus* Zimmerman) is critical to the management of high value hardwood plantations in the Central Hardwood Forest Region. One-year-old black walnut (*Juglans nigra* L.), northern red oak (*Quercus rubra* L.), and white ash (*Fraxinus americana* L.) bareroot seedlings were outplanted into a replicated experimental design on a field planting site in southern Indiana at Purdue University's Southeast Purdue Agricultural Center in April 2003. Five simulated summer browse treatments were applied to 15 seedlings of each species within each of five blocks, plus a control treatment for each, and were monitored for two growing seasons. Northern red oak exhibited the highest mortality rates in both years; only the most intense clipping treatment resulted in reduced mortality in year 2 in contrast to the control treatment. Seedlings with clipped terminals exhibited no height or root collar diameter (RCD) growth differences in any species. Treatments that removed leaf biomass resulted in reduced height and RCD growth in both years in contrast to control treatments, but exhibited few differences across intensity of treatments, although trends indicated that multiple clippings in a single season exhibited lower growth rates. Our findings suggest that browsing could cause significant variation in growth rates among these species, and that species composition may be altered as a result of repeated browse events.

INTRODUCTION

The effects of browsing on plantation seedling performance are believed to negatively impact their growth, form, height, and to reduce survival. The response of seedlings varies by species, the timing, intensity, and frequency of browsing, and the available resources for seedling growth; these factors may ultimately result in altered species composition (Metzger 1977, Anderson and Loucks 1979, Marquis and Brenneman 1981, Frelich and Lorimer 1985, Pastor and others 1988, Rossell and others 2005). Morphological traits, such as heterophyllous shoots within buds (Metzger 1977), and physiological traits, including carbohydrate storage and allocation patterns (Kays and Canham 1991), may contribute to the varied responses to browsing. Winter browsing results in the loss of structural material used to support growth in the following growing season, although plants may be more tolerant of browsing because carbohydrate reserves are stored throughout the plant tissue. While seedlings browsed during the summer may lose both leaf area and woody tissue required to produce carbohydrate reserves at a time when reserved stores are low, they may be more sensitive to browse during the growth period. Low to intermediate levels of browse have been shown to result in increased height growth in some species (Metzger 1977, Welch and others 1992, Edenius and others 1993), while more extreme levels of browsing have been shown to result in decreased growth and survival (Campa and others 1992). Successive years of browsing seem to decrease a seedling's ability to respond to browse (Canham and others 1994). While the response of seedlings to browsing under variable site conditions is not fully understood (Belsky 1987, Maschinski and Whitham 1989, Oesterheld and McNaughton 1991), it is expected that seedling responses will exhibit variation in the type and degree of response to browsing across different sites.

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The response of browsed seedlings is critical to the management of high-value hardwood plantations in the Central Hardwood Forest Region (CFHR). White-tailed deer (*Odocoileus virginianus* Zimmerman) are of particular concern in the region because of the large population densities found today (McCabe and McCabe 1984) and shrinking traditional forest foraging sites, such as early successional forest communities. Most browsing occurs in the dormant season (fall, winter, and spring), when carbohydrate reserves are stored throughout the plant. However, though typically less common, summer browsing may prove to be particularly harmful to seedlings. Canham and others (1993) observed that seedlings not shaded by adjacent shrubs and herbs had a higher probability of being browsed, thus making plantation settings particularly vulnerable. They speculated that they may be more tolerant of browse because of high rates of photosynthesis in low-competition and high-light environments. Monocultures of certain species may be devastated by repeated browsing. Mixed plantations will likely exhibit a varied species response, possibly resulting in altered species composition, spatial distribution, and competitive pressures.

OBJECTIVES

The objective of this study was to evaluate the effects of varying intensity of summer browse levels, as simulated by mechanical clipping, on the growth and survival of three important tree species of high value hardwood plantations in the CHFR.

STUDY AREA

The study site was located at the Southeast Purdue Agricultural Center in Indiana (39°01′ N, 85°35′W). Soil is primarily classified as a Muscatatuck series (fine-silty, mixed, active, mesic, Fragic Hapludalf) (USDA NRCS Pedon I.D. S021IN-079-001), formed in forest vegetation with a visible plow layer (Soil Survey Staff 2004).

METHODS

One-year-old bareroot seedlings (1+0) grown in 2002 under standard nursery cultural practices at the Indiana Department of Natural Resources State Tree Nursery near Vallonia, IN (38°85′ N, 86°10′W) were planted in April 2003. Three tree species were selected for study—black walnut (*Juglans nigra* L.), northern red oak (*Quercus rubra* L.), and white ash (*Fraxinus americana* L.)—because all are commonly used in plantations throughout the CHFR. Their abundance and value make them appropriate species for examination. LaGory and others (1985) indicated a lack of selectivity in woody species selection by foraging deer in natural regeneration settings during winter; thus, it is assumed all species are equally susceptible to browse pressure.

Seedlings from the resultant 18 treatments (three species x six simulated browse treatments) were machine planted into a randomized complete block design replicated in five blocks. Fifteen seedlings from each treatment were planted into each block (1.22-m spacing) for a total of 1,350 seedlings in the experiment. Treatments consisted of: 1) control treatment with no clipping (CTRL); 2) clipped terminal bud before leaf out (CT); 3) 50-percent reduction in leaf biomass early in the growing season (50RLB); 4) 75-percent reduction in leaf biomass early in the growing season(75RLB); 5) 25-percent reduction in leaf biomass early in the growing season and another 50-percent reduction in remaining leaf biomass in the middle of the growing season (25-50RLB); and 6) 50 percent reduction in leaf biomass early in the growing season and another 75 percent reduction in remaining leaf biomass in the middle of the growing season (50-75RLB) (Table 1). Seedlings were clipped using a hand pruner at varying levels of intensity in both growing seasons. An electric deer fence was installed immediately after planting and maintained throughout the experiment.

Table 1.—Simulated browse treatment codes, descriptions, and application dates

Code	Description	2003	2004
CTRL	no browse		
CT	Clipped terminal prior to leaf-out	10-Apr	21-Apr
50RLB	Post leaf-out 50% reduction in leaf biomass	21-May	7-Jun
75RLB	Post leaf-out 75% reduction in leaf biomass	21-May	7-Jun
25-50RLB*	Post leaf-out 25% reduction in leaf biomass; later in the season another 50% reduction in leaf biomass	16-Jul	12-Jul
50-75RLB*	Post leaf-out 50% reduction in leaf biomass; later in the season another 75% reduction in leaf biomass	16-Jul	12-Jul

*Dates listed apply to the second clipping within that year; first clipping treatments were administered on the same day as the 50RLB and 75RLB treatments.

Table 2.—Analysis of variance for height and root collar diameter growth, and survival for the randomized complete block design using species (SP) and clipping treatments (TRT) as factors

		P > F		
Year	Source of variation	Height	RCD	Survival
1	SP	< 0.0001	0.0838	< 0.0001
	TRT	< 0.0001	0.0245	0.2820
	SP x TRT	< 0.0001	0.0177	0.5165
2	SP	< 0.0001	< 0.0001	< 0.0001
	TRT	< 0.0001	< 0.0001	0.0475
	SP x TRT	< 0.0001	< 0.0001	0.5678

Glyphosate (Round-up®, 3.5 L ha^{-1}), and simazine (9.35 L ha^{-1}) were applied annually to attain maximum weed control and minimize competition for moisture and nutrients from non-crop vegetation. Seedling field survival, total height (ground level to base of last surviving bud), and root collar diameter (RCD) were measured immediately after planting and at the end of each of the two growing seasons reported in this study.

Data were analyzed using analysis of variance (ANOVA) to determine if mean (± standard error) annual survival, height, and RCD growth data differed among treatments. Initial height and RCD were tested using ANOVA for each species by treatment with no significant differences detected. When factor effects were significant, means were ranked according to Tukey's honestly significant differences test; differences were considered significant at $P \leq 0.05$. All data were analyzed using SAS Version 9.1 (SAS Institute Inc. Cary, NC 2004).

RESULTS

Seedling Survival

Mean seedling survival differed among species in both years ($P < 0.0001$), but differed among treatments only in year 2 ($P < 0.0269$) (Table 2). Northern red oak had the highest mortality rates of all species in both years, 7±1 percent in year 1 and 16±3 percent in year 2 (data not shown), while black walnut and white ash exhibited considerably less mortality overall. In year 2, there were no differences among clipped

Table 3.—Mean height, root collar diameter, and seedling mortality by species and treatment after two growing seasons. Different lower case letters within each species indicate significantly different means between treatments

Treatment	Height (cm)		RCD (mm)		Mortality (%)	
			Black walnut			
CTRL	103.9	a	23.6	a	4.0	a
CT	85.2	ab	19.8	ab	10.6	a
50RLB	97.0	a	22.9	ab	1.4	a
75RLB	71.6	bc	18.5	b	9.4	a
25-50RLB	50.7	cd	13.1	c	6.8	a
50-75RLB	44.9	d	12.5	c	12.2	a
			Northern red oak			
CTRL	59.0	a	8.8	a	9.2	a
CT	46.8	ab	8.0	ab	17.4	a
50RLB	37.5	bc	6.7	bc	16.0	a
75RLB	39.3	bc	6.9	bc	30.8	a
25-50RLB	36.7	bc	6.7	bc	25.4	a
50-75RLB	30.6	c	5.8	c	33.2	a
			White ash			
CTRL	158.6	a	27.1	a	0.0	a
CT	123.9	ab	23.0	ab	1.4	a
50RLB	93.3	bc	17.3	bc	5.4	a
75RLB	102.2	bc	19.2	bc	1.4	a
25-50RLB	74.1	c	15.0	c	1.4	a
50-75RLB	67.0	c	14.7	c	5.4	a

seedlings, but the most intense browse treatment, 50-75RLB, had higher mortality compared to the control treatment. Although the species and treatment interactions were not considered significant in year 2, trends would seem to indicate that northern red oak had greater mortality within all treatments (Table 3).

First Year Seedling Growth

Species, treatment, and their interaction resulted in differing seedling height growth in year 1 (all $P < 0.0001$), while treatment effects and interactions between species and treatments yielded differences in RCD growth ($P = 0.0245$ and $P = 0.0177$, respectively) (Table 2). Northern red oak exhibited very limited height growth in year 1; all treatments, with the exception of the clipped terminal treatment, displayed reduced growth rates in contrast to the control seedlings (Fig. 1). Northern red oak RCD exhibited no positive growth within any treatments in year 1, including seedlings that were not clipped (Fig. 2). Black walnut height growth rates were also low in year 1 and showed no differences among treatments in year 1 growth rates (Fig. 1); RCD growth showed very mixed growth rates and no differences across all treatments in year 1 (Fig. 2). White ash height growth rates in year 1 were generally greater (averaging 21.2±2.4 cm) than both black walnut and northern red oak (5.3±1.2 cm and -1.2±0.83 cm, respectively) among all treatments. Reduced growth rates occurred in only those treatments where leaf biomass was removed (Fig. 1), and all treatments that removed leaf biomass showed no positive RCD growth rates in white ash in year 1 (Fig. 2).

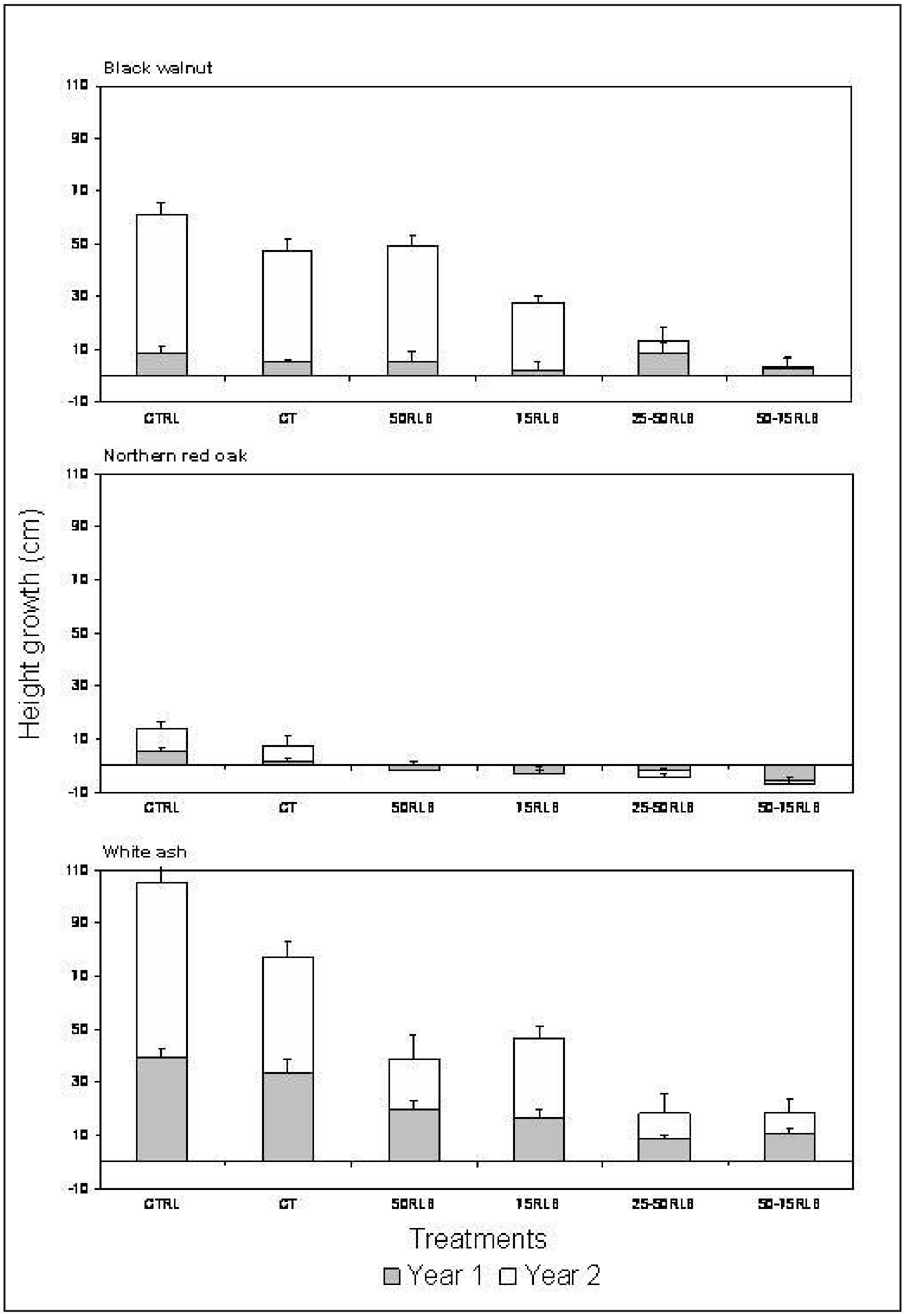

Figure 1.—Mean (± standard error) annual height growth rates of black walnut, northern red oak, and white ash seedlings by treatment for years one and two.

Second Year Seedling Growth

Species and treatment factors, and their interactions, in year 2 were highly significant for both seedling height and RCD growth (all $P < 0.0001$) (Table 2). Northern red oak exhibited very limited height growth again in year 2 with a similar trend of only the control and CT treatments exhibiting positive growth and no differences among all other treatments (Fig. 1). Northern red oak RCD growth rates were higher in year 2 with no differences between treatments that removed leaf biomass. Black walnut height and RCD growth rates were greater across most treatments in year 2 compared to year 1, although successive clipping treatments within year 2 resulted in lower growth rates of both measures when compared to all other treatments (Figs. 1 and 2). White ash height growth rates in year 2 appeared similar to those of year 1 across all treatments (Fig. 1), but those treatments where leaf biomass was removed exhibited lower height growth rates than white ash control treatment seedlings. RCD growth of white ash in year 2 was higher

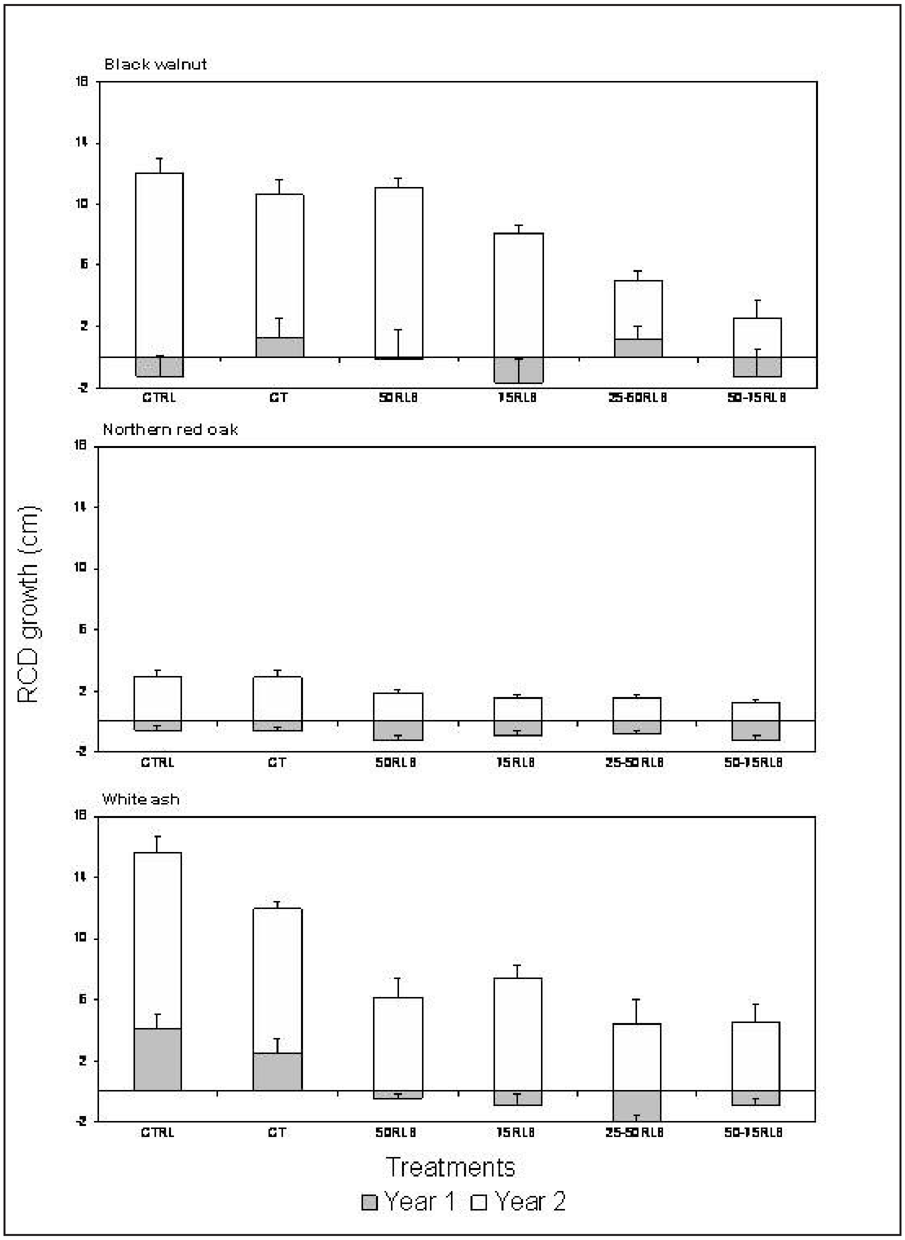

Figure 2.—Mean (± standard error) annual root collar diameter growth rates of black walnut, northern red oak, and white ash seedlings by treatment for years 1 and 2.

relative to year 1 across most treatments, but was lower for treatments with leaf biomass removal, with the exception of the 75-percent RLB treatment (Fig. 2).

DISCUSSION

In our study, the effects of simulated browsing had little effect on mortality, with the exception of only the most intensive browse treatment in year 2, while interspecific differences in mortality were evident in both years. Simulated browse treatments did, however, exhibit differences in total height and RCD growth, as well as annual growth rates. Although all intensities of treatments that removed leaf biomass differed from the control treatment, they typically were not different when compared to one another. This result suggests that summer browse levels that remove 50 percent or more of leaf biomass can negatively impact seedling growth for all species studied, and that each species may react differently to browse treatments.

Northern red oak had the highest mortality rates of all species in both years; while in year 2 the most intense simulated browse treatment, 50-75RLB, exhibited higher mortality than seedlings that were not clipped. Short-term effects of simulated browse indicate that resultant reduced growth rates and interspecific differences of mortality will likely result in altered species composition of mixed species plantations. Similar results have been documented in natural stands. Rossell and others (2005) concluded that white-tailed deer browsing altered structure and species composition across several forest types over a 5-year period in Virginia, with red and white oak group members greatly reduced, while ash and black cherry (*Prunus serotina* Ehrh.) remained abundant.

Simulated browsing resulted in different responses between species and treatments. Those treatments involving removal of leaf biomass generally resulted in decreased growth rates of height and RCD among all species, most noticeably in year 2. The clipped terminal treatment (CT) resulted in no differences in any species for height and RCD growth in either year 1 or year 2 (Figs. 1 and 2) or final height and RCD (Table 3), when compared to seedlings that were not clipped. Hjältén and others (1993) found similar results in juvenile downy birch (*Betula pubescens* Ehrh.) after varying levels of simulated browse treatments. While the removal of the terminal may break apical dominance, Aarssen and Irwin (1991) suggested that the removal of the terminal bud may in fact act as a benefit to a tree grown in a low-density situation, such as a plantation setting. Temporarily, these trees are apically indeterminate and could branch to fully utilize the available growing space. Aarssen and Irwin's (1991) hypothesis may explain the lack of differences between control seedlings and seedlings with clipped terminals. However, the differences observed, most noticeably in year 2 and in the more intense clipping treatments, may be related to the more intense leaf biomass removal treatments that resulted in less leaf area and photosynthetic capacity, and thus, reduced ability to respond to simulated browse. The timing of the initial browse events (Table 1) would also leave less time for recovery and result in reduced growth, most notably in those seedlings clipped twice within a single growing season.

The capacity for seedlings to recover from browse damage is strongly related to the timing of damage and the type of damage incurred (Jameson 1963, Maschinski and Whitham 1989, Hjältén and others 1993). Successive defoliation treatments of all species within year 1, 25-50RLB and 50-75RLB, resulted in no significant differences in height and RCD growth when compared to the less intense leaf biomass removal treatments, 50RLB and 75 RLB. However, in year 2, black walnut showed reduced growth rates of height and RCD with successive defoliation. This response implies that black walnut could not compensate for the continual heavy losses of photosynthetic capacity. Both northern red oak and white ash exhibited no differences when compared to the single defoliation treatments, although all leaf biomass removal treatments resulted in lower growth rates and smaller final height and RCDs compared to unclipped seedlings. With the exception of black walnut in year 2, the lack of differences among treatments within species in height and RCD growth implies that simulated browse events that remove 50 percent or more of leaf biomass, either in a single or two separate browse events throughout the summer, will result in reduced growth rates. The translocation of nutrients from the leaves of hardwood seedlings to the roots at the end of the growing season would also be limited in proportion to the amount of leaf biomass lost, thus contributing to reduced nutrient storage and growth rates in the following year. Although there were few differences between treatments within species in the short-term, trends indicate that more intensive treatments, 25-50RLB and 50-75RLB, exhibit lower growth rates, which would likely become more significant in the future as the effects are compounded over time.

Under low-intensity browse treatments, CT, 50RLB, and 75RLB, white ash exhibited more height growth than black walnut and northern red oak in year 1. In year 2, black walnut and white ash showed no significant differences. Slower-growing species, such as northern red oak relative to black walnut and white ash, generally tolerate browsing less than fast-growing species, especially under repeated browse events (Côté and others 2004). Trends in our data would seem to confirm such differences.

Our findings suggest that northern red oak seedlings in plantation settings subject to moderate to heavy browsing exhibit lower rates of growth. Repeated browsing may serve to alter the relative competitive success of seedlings of varying species to grow above the level of browsers such as white-tailed deer, in turn altering composition of plantations in the future as other more browse-resistant species, such as white ash, continue to grow. Our findings suggest that browsing could cause significant variation among these species, and that species composition may be altered as a result of continuous browse events. Depending on landowners' objectives and site factors, some form of seedling protection (e.g., fencing, tree shelters) may be warranted to enhance the prospects of successfully establishing planted seedlings.

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DISKING AND MID- AND UNDERSTORY REMOVAL FOLLOWING AN ABOVE-AVERAGE ACORN CROP IN THREE MATURE OAK FORESTS IN SOUTHERN INDIANA

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Abstract.—We disked using small-scale equipment in the understory of three mature upland oak (*Quercus*) forests in southern Indiana immediately following acorn dispersal in an above-average seed crop year as a means of improving oak seedling establishment. Three different mid- and understory removal treatments were also applied to create favorable light conditions for the new cohort of oak seedlings. Disking increased the number of new oak seedlings by 14,586 per hectare. There were nearly 2¾ times more 2006 cohort oak seedlings in the disked areas than in nondisked areas. Both the injection and girdling mid- and understory removal treatments increased the estimated first-year seedling survival by 48 percent and 80 percent, respectively, over survival in the no treatment control. The basal bark treatment resulted in significantly fewer (63 percent) estimated surviving seedlings than the control treatment. Only two damage agents proved significant in reducing oak seedling numbers. Of 700 dead oak seedlings tallied at the end of the first growing season, 411 (59 percent) were killed by herbicide exposure resulting from volatilization of triclopyr in the basal bark treatment. An additional 135 (19 percent) seedlings were killed by pine voles. Deer browse and insect and disease damage proved inconsequential. Pine voles, which tunnel and feed on seedling roots and stems, are implicated in the majority of unaccounted-for oak seedling mortalities where the seedlings disappeared entirely.

INTRODUCTION

Acorn loss to predation and environmental extremes greatly reduces the number of acorns available for oak (*Quercus*) seedling establishment. Most viable acorns can be consumed by predators in years of low to moderate acorn production (Crow 1988). The impacts of white-tailed deer (*Odocoilus virginianus*) and rodent predation on oak seedling establishment are well documented (Steiner 1995, Ostfeld and others 1996). Soil scarification timed to coincide with end of acorn dispersal in the fall may reduce some loss of acorns to predation and environmental extremes and result in the establishment of substantially more oak seedlings on a site (Lhotka and Zaczek 2003).

Timely removal of shade-tolerant mid- and understory canopy layers prior to or following acorn dispersal is important to the establishment and survival of a cohort of oak seedlings. In undisturbed mature oak forests with well developed shade-tolerant mid- and understory canopy layers, more than 70 percent of planted oak seedlings died within 5 years of planting (Lorimer and others 1994). Loftis (1983) found that survival of a cohort of northern red oak (*Q. rubra* L.) seedlings in undisturbed oak forests in the southern Appalachians after 12 years was less than 10 percent. In order for new oak seedlings to develop into competitive oak advance reproduction, optimum understory light conditions must be obtained. Thinning from below to 60 to 70 percent of initial stand stocking, starting with the shade-tolerant mid- and understory may provide the optimum light levels required to establish competitive oak seedlings prior to overstory removal (Loftis 1990, Larsen and Johnson 1998).

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OBJECTIVES

The purpose of this study was to determine if oak seedling establishment from acorns was affected by scarification in combination with mid- and understory canopy removal. We tested the use of small-scale equipment to disk-scarify the soil to bury acorns while removing the shade-tolerant mid- and understory canopy layers in mature oak forests.

METHODS

The study was established in October 2005 in three 1.62-hectare blocks located in three different forest tracts (tracts I, N, and P) at the Southern Indiana Purdue Agricultural Center located in south-central Indiana. Each tract's overstory was dominated by mature oak, primarily white (*Q. alba* L.), northern red, and black oak (*Q. velutina* Lam.). Side-by-side paired transects were marked to facilitate efficient disking. Of each pair, one was designated to be disked and the other a nondisked control. These transects ranged from 46 m to 152 m in length and were spaced approximately 5 m to 9 m apart depending on block layout and topography.

Sound acorns were counted and identified to species using a 0.6 m x 0.6 m square sample frame at 9-m intervals along transects designated to be disked. Each acorn sample point was permanently marked. Soundness of acorns was determined using visual and tactile examination. Only fully mature acorns were counted as sound. Acorns with weevil exit holes, with caps still attached, with discolored cap attachment points, or which felt dried out or hollow when handled were not counted as sound. From Oct. 27 to Nov. 1, 2005, acorns were sampled in transects designated to be disked, but were not sampled in adjacent paired nondisked transects. In addition to acorns, advance oak reproduction established prior to fall 2005 was inventoried using the same sample plots.

Designated transects were disked on Nov. 1, 2005, using a 1.8-m wide double-row disk drawn by a 24-hp John Deere 855 4x4 diesel tractor with extra weight mounted to the front end. This size of tractor provided good maneuverability in forest settings with less than 10 percent slopes and required very minimal cutting of logs or understory trees. Disked transects were 1.8-m wide and disked to a depth of 7.6 to 15.2 cm.

Paired 1-m^2 sample plots were established and permanently marked at the same permanently marked acorn sampling plots. Paired sample plots were located within 1.5 m of each other, so that each was underneath the same tree crown, and so one was located in the disked transect and one in the paired nondisked transect. Oak seedlings were inventoried four times to track changes through the first growing season: May 25-31, July 17-24, August 23-31, and Oct. 12-18. Oak seedlings were tallied by species and by whether they were new germinants or older seedlings at each paired sample plot on each paired transect using a 1-m^2 sample frame. Dead seedlings were also tallied and cause of death, where identifiable, was noted. The corners of the sample frame were permanently marked so that the exact same plot location could be sampled each time.

Each 1.62-ha block was divided into four 0.41-ha plots and randomly assigned one of four different methods for controlling mid- and understory woody vegetation as means for ensuring adequate levels of light in the understory to sustain oak seedlings. The methods were 1) injection using an ax with a 4.4-cm bit and Pathway[2] herbicide delivered to injections using a backpack sprayer and gunjet nozzle; 2) chainsaw

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[2]Garlon 4 and Pathway are registered tradenames of Dow AgroSciences.

girdle and felling with the application of Pathway to the girdle or cut stump; 3) low volume basal bark using the ester formulation of triclopyr (Garlon 4[2]) diluted to 20 percent concentration in a paraffinic petroleum distillate basal oil (AX-IT[3]); and 4) a no-removal control treatment. The objective of the mid- and understory removal was to remove the low shade component of the canopy while maintaining intact the high shade component. All mid- and understory trees greater than 1.27 cm diameter at breast height (d.b.h.) were treated, with the exception of a small number of oaks or occasional shade-tolerant trees growing in natural canopy gaps. These mid- and understory removal treatments were applied from June 29 to July 7, 2006. The efficacy of these treatments is not described here. However, their influence on oak seedling establishment was tested in this analysis.

A generalized linear model of the form:

$$y_i \sim \text{Overdispersed Poisson}\left(\mu_i e^{\mathbf{X}_i \boldsymbol{\beta}}, \omega\right)$$

was fit to the number of live seedlings surviving to October (y_i), 2006 in each sample plot i. This model is essentially an analysis of covariance (ANCOVA), except that errors are assumed to be Poisson, rather than normally, distributed. The Poisson model is more appropriate for count data. The predictors (X_i) included tree species (white oak, northern red oak, and black oak) as well as disking (nondisked versus disked), mid- and understory removal treatments (no-removal control, herbicide injection, girdling, and basal bark herbicide application) and tract (I, N, and P). The regression coefficient associated with each treatment combination (β) represents a multiplicative change in the probability that an acorn present in November will germinate and survive to the following October, relative to the survival rate for white oak in nondisked, no-removal control mid- and understory removal sub-plots (i.e. the intercept) (Gelman and Hill 2007). We accounted for differences in background acorn density among plots by entering the November 2005 acorn counts for each species as a covariate (μ_i). Acorn counts were extrapolated to acorns/m^2 and rounded to the nearest whole number to ease interpretation. Omega (ω) is a scale parameter, and does not affect the regression fit. In this hierarchical design, the experimental unit is the finest level of resolution for which the data were collected, in this case, the 1 m^2-sample plot. To account for problems associated with potential pseudoreplication, sample plot, transect line, and tract were initially included in the model as predictor variables to test for random effects. Random effects due to sample plot and transect line proved insignificant. However, there were differences between tracts and thus tract was kept as a predictor in the final model.

A full-factorial model was fit initially, including all possible interaction terms. Interaction terms were subsequently dropped if none of the associated regression coefficients were significant ($\alpha = 0.05$). Data were reported as observed seedling densities. Similar methods were used to analyze the number of mortalities due to herbicide exposure and rodent predation. Analyses were performed in R, version 2.5.1 (R Development Core Team 2007).

RESULTS AND DISCUSSION

Acorn Density and Distribution

Across all three tracts, the number of sound acorns in November 2005 for each of the three oak species was roughly proportional to the overstory basal areas for each species (Tables 1 and 2). Tract P had a disproportionately large number of white oak (WO) acorns compared to red oak (RO) and black oak (BO), whereas Tract I had a disproportionately large number of RO acorns compared to WO, with a very

[3]AX-IT is a registered trade name of Townsend Chemical.

Table 1.—Stand overstory basal area for three mature upland oak stands (I, N, and P) in southern Indiana receiving strip disking and mid- and understory removal treatments

	Tract			
Stand stocking	I	N	P	Mean
Overstory basal area		(m^2/ha)		
White oak	4	9	22	13
Red oak	10	6	2	7
Black oak	1	2	1	1
Total oak	15	17	25	21
Other species	17	7	4	10
Total overstory	32	24	29	31
Mid- and understory basal area	6	5	7	6
Total basal area	38	29	36	37

Table 2.—Observed numbers of acorns sampled shortly after dispersal in Nov. 2005 for three mature oak stands (I, N, and P) in southern Indiana receiving disking and mid- and understory removal treatments

	Tract			
Species	I	N	P	Mean
		(acorns/ha)		
White Oak	35,609	59,124	162,471	92,784
Red Oak	132,725	77,064	14,089	66,405
Black Oak	4,856	40,932	11,170	21,026
Total Oak	173,190	177,121	187,730	180,214
(n) 0.372 m^2 sample plots	133	213	212	558

minor component of BO. Tract N acorn numbers were more evenly distributed among the three species, RO accounting for a small majority of the total acorn count (44 percent). Total acorn numbers irrespective of species showed a fairly even distribution among the three tracts. An average across all three tracts of more than 180,000 acorns per hectare of all three species combined was estimated to be on the ground at the time of disking (Table 2). Lhotka and Zaczek (2003) reported 195,500 to 212,600 acorns per hectare on the ground in an oak-hickory stand in southern Illinois prior to soil scarification. Bundy and others (1991) reported 151,000 acorns on the ground in a mixed hardwood stand in southeastern Minnesota. Within tracts, acorn distribution was patchy, reflective of the patchy distribution of seed-bearing parent trees. More than 20 percent of the 558 0.372 m^2 sample plots contained no acorns, with more than 50 percent contained three or fewer acorns. More than 20 percent of sample plots contained 10 or more acorns, the equivalent of more than 270,000 acorns per hectare, with one sample plot containing 79 acorns. Steiner (1995) found that RO acorn numbers ranged from 1,300 to 490,518/ha with an average of 103,236/ha across four consecutive years and five widely separated stands in Pennsylvania. Because of the patchy distribution of acorns and uneven distribution between midstory removal treatment areas, sampled numbers of acorns were used as a covariate in the generalized linear model.

Oak Seedling Treatment Responses

Oak reproduction established before fall 2005 was scarce to nonexistent over much of each of the three tracts. Only 16 out of 558 pretreatment (0.372-m^2) sample plots had oak advance reproduction, which

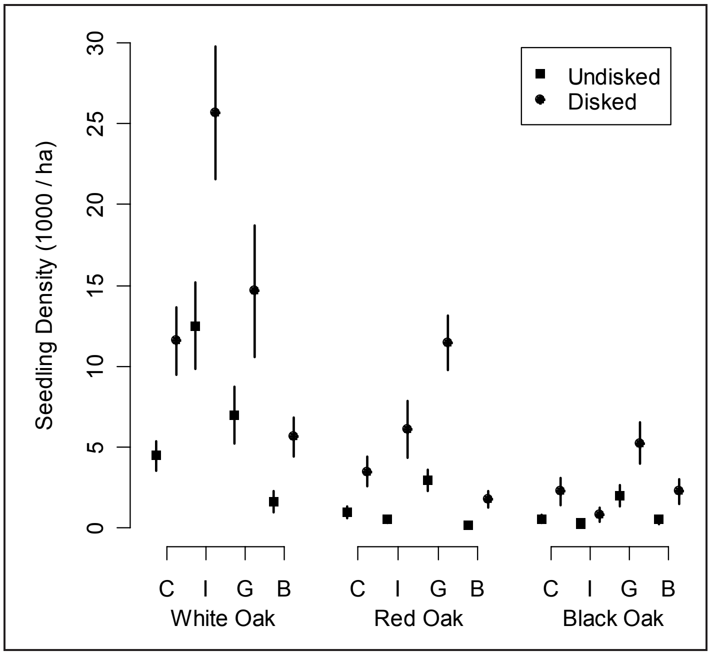

Figure 1.—Mean effects of disking and mid- and understory removal treatments on the density of a first-year cohort of oak seedlings growing in three mature oak stands in southern Indiana. Mid- and understory removal treatments were: no-removal treatment/control (C); herbicide injection (I); girdling and felling (G); and basal bark herbicide application (B).

may be extrapolated to 868 oak seedlings/ha. Post treatment, 6 out of 557 1-m^2 sample plots (143 oak seedlings/ha) in the disked areas had pre-fall 2005 oak advance reproduction, while 13 of 554 (326 oak seedlings/ha) nondisked sample plots did.

Overall, there were fewer RO and BO than WO 2006 cohort seedlings surviving to October 2006 (Table 3, Fig. 1). However, there were no differences in the rate of survival between the three species relative to the number of acorns occurring for each (Table 4). Significant tract differences also occurred. Tract P had 78 percent more oak seedlings/ha than tract N, which had 66 percent more than tract I (Table 3). Proportional differences in seedling densities among the three oak species also occurred between tracts, reflecting overstory basal area (Table 1) and acorn numbers (Table 2). Only one species by tract interaction proved significant. RO seedling density in tract P compared to the other two oak species in that tract was lower relative to RO seedling densities compared to the other oaks in the other tracts (Table 4). However, there were no differences between the species in their response to either disking or the midstory control treatments as indicated by a lack of significant interaction between these factors.

Disking significantly increased the likelihood that sound acorns on the ground in the fall resulted in live oak seedlings following the first growing season, compared to acorns falling in nondisked areas (Table 4). P-values in Table 4 less than 0.05 indicate significant treatment differences. Disking increased the number of new oak seedlings by 14,586 per hectare. There were nearly 2¾ times more 2006 cohort oak seedlings in the disked areas than in nondisked areas (Table 5). Other studies have found that soil scarification increases short-term oak seedling establishment relative to nonscarified controls. Scholz (1959) reported a 2.4-fold increase in RO seedlings in scarified plots versus nonscarified 2 years following treatment. Seven years following treatment, however, there were no differences in numbers of oak seedlings between scarified and nonscarified plots. Bundy and others (1991) reported no significant differences in RO seedling establishment between scarified and nonscarified treatment areas in a southeast Minnesota mixed hardwood forest. Lhotka and Zaczek (2003) found that scarification resulted in 5,100 oak seedlings per hectare versus 1,300 per hectare without scarification, a threefold increase, 1 year after treatment.

Table 3.—Observed density of 2006 cohort oak seedlings surviving to October 2006 for three mature oak stands (I, N, and P) in southern Indiana averaged across disking and mid- and understory removal treatments

	Tract			
Species	I	N	P	Mean
	(seedlings/ha)			
White Oak	603	1795	8942	4132
Red Oak	2534	1942	189	1439
Black Oak	77	1594	368	787
Total Oak	3214	5331	9499	6358
(n) 1-m^2 sample plots	262	442	407	1111

Table 4.-Estimated overdispersed Poisson regression coefficients for the effects of tree species, disking, understory treatment, and tract on oak seedling density (n = 3192, ω = 3.9, percent deviation explained = 29%)

		Estimate	SE	t	p-value
(Intercept)		-5.0832	0.5068	-10.03	<0.001
Species	Red Oak	0.0373	0.356	0.1	0.916
	Black Oak	-0.7958	0.9367	-0.85	0.396
Disking	Disked	1.9741	0.4201	4.7	<0.001
Understory	Injection	0.4438	0.1577	2.82	0.005
	Girdling	0.6545	0.1456	4.5	<0.001
	Basal Bark	-0.9797	0.2049	-4.78	<0.001
Tract	Tract N	1.7303	0.529	3.27	0.001
	Tract P	2.3414	0.5033	4.65	<0.001
Interactions	Red Oak : Tract N	-0.3937	0.4133	-0.95	0.341
	Black Oak : Tract N	0.5708	0.9637	0.59	0.554
	Red Oak : Tract P	-2.0319	0.5816	-3.49	<0.001
	Black Oak : Tract P	-0.0542	0.993	-0.05	0.956
	Disked : Tract N	-1.0421	0.4604	-2.26	0.024
	Disked : Tract P	-1.084	0.443	-2.45	0.014

Table 5.—Mean observed density of 2006 cohort oak seedlings surviving to October 2006 by disking treatment across three mature oak stands in southern Indiana. Different letters within columns indicate significant differences at α=0.05.

Disk treatment	WO	RO	BO	TOT
	---------------------------(seedlings/ha)---------------------------			
Disked	14093 a	5853 a	3034 a	22980 a
Not disked	6300 b	1245 b	848 b	8393 b

Table 6.—Estimated overdispersed Poisson regression coefficients for the effects of tree species, disking, and understory treatment on the number of seedlings killed by herbicide in their first year (n = 3192, ω = 0.53, percent deviation explained = 63%)

		Estimate	Std. Error	t	P-value
(Intercept)		-22.08	610.93	-0.04	0.971
Species	Red Oak	-18.39	490.24	-0.04	0.970
	Black Oak	-2.77	0.30	-9.27	<0.001
Disking	Disked	0.29	0.07	3.99	<0.001
Understory	Injection	16.61	610.93	0.03	0.978
	Girdling	0.04	797.55	0.00	1.000
	Basal Bark	19.66	610.93	0.03	0.974

Mid- and understory treatments removed between 15 percent and 19 percent of the total stand basal area in the three tracts. Both the injection and girdling mid- and understory removal treatments appeared to have a positive effect on first-year oak seedling survival (Table 4 and Fig. 1), increasing it by 48 percent and 80 percent, respectively, over survival in the no-removal control treatment. The basal bark treatment resulted in significantly fewer (63 percent) surviving seedlings than the control treatment (Fig. 1). A number of studies demonstrate that oak seedlings have poor survival in the low light conditions present in mature oak stands with shade-tolerant mid- and understories (Lorimer and others 1994, Crow 1988). Janzen and Hodges (1985) found that mid- and understory removal using injection and foliar herbicide applications in a mature southern bottomland oak stand increased numbers of new oak germinants by 100 percent 3 years after treatment. Loftis (1990) proposed methods for regenerating northern red oak in the southern Appalachians through thinning from below. In many stands much of the required basal area removal can be accomplished by removing the midstory and understory canopy layers. When these layers are removed while keeping much of the overstory intact, sufficient light reaches the forest floor to maintain oak seedling development. These light levels, however, are insufficient to maintain the growth and establishment of many of the oak seedlings' shade-intolerant competitors, such as yellow-poplar (*Liriodendron tulipifera* L.).

Oak Seedling Mortality

Mortality data represented only those dead seedlings that were actually observed and counted, and thus do not account for the number of seedlings that disappeared between sample dates. Two causes of mortality were readily observed: herbicide damage and pine vole (*Microtus pinetorum*) predation. Because of the relatively small number of herbicide-induced mortalities compared to the large number of sample plots, variability was too high to detect treatment differences in the model (Table 6). However, observationally, the effects were obvious, with quite complete oak seedling mortality occurring in concentrated areas of the basal bark treatment plots. Of the 700 dead oak seedlings tallied, 411 (59 percent) were killed by herbicide exposure. Herbicide-induced mortality occurred almost exclusively (96 percent) in the basal bark treatment. Although not well documented in the scientific literature, triclopyr herbicide in its ester formulation may volatilize at air temperatures exceeding 28 °C. Rathfon and Ruble (2006) showed reductions in Amur honeysuckle control when basal bark treatments using the ester formulation of triclopyr were applied at air temperatures reaching 33 °C. High temperatures on the dates of the basal bark treatment application in this study exceeded 28 °C. Volatilized triclopyr very likely injured oak seedlings, resulting in significantly fewer oak seedlings in the basal bark treatment compared to all other midstory

Table 7.—Estimated overdispersed Poisson regression coefficients for the effects of tree species, disking, understory treatment, and tract on the number of seedlings killed by pine voles in their first year (n = 3192, ω = 1.0, percent deviation explained = 15%)

		Estimate	SE	t	p-value
(Intercept)		-9.0794	1.0725	-8.47	<0.001
Species	Red Oak	1.925	1.0214	1.88	0.059
	Black Oak	1.1131	1.4155	0.79	0.432
Disking	Disked	1.4748	0.2263	6.52	<0.001
Understory	Injection	0.9595	0.3938	2.44	0.015
	Girdling	1.4487	0.3475	4.17	<0.001
	Basal Bark	0.9298	0.3899	2.38	0.017
Tract	Tract N	1.0509	1.0835	0.97	0.332
	Tract P	2.1426	1.0122	2.12	0.034
Interactions	Red Oak : Tract N	-0.885	1.1278	-0.78	0.433
	Black Oak : Tract N	0.0919	1.4979	0.06	0.951
	Red Oak : Tract P	-2.3771	1.1505	-2.07	0.039
	Black Oak : Tract P	-2.837	1.7379	-1.63	0.103

removal treatments (Fig. 1). However, early observations of seedling survival in the second growing season indicate that some oak seedlings tallied as dead due to herbicide exposure resprouted.

Pine vole activity was evident in all three tracts, primarily indicated by tunnels close to the soil surface and by exit holes. The majority of total mortality could not be identified with certainty because the seedlings disappeared altogether. Pine vole-induced mortality was observed when dead seedlings were easily pulled from the ground, revealing that the roots had been eaten off, or when dead seedling tops were found lying on the soil surface. This evidence was almost always found in combination with pine vole burrows on the sampled plot. Nineteen percent of tallied oak seedling mortality was due to pine vole predation. Seedling predation by species did not differ statistically (Table 7). Although there were 65 percent fewer RO seedlings than WO seedlings throughout all tracts and treatments, pine vole predation was not significantly different between the two species, indicating a disproportionate level of predation on RO seedlings versus WO seedlings. This result may indicate pine vole feeding preferences or it may only reflect closer proximity of RO versus WO seedlings to the pine voles. Seedlings in disked plots suffered increased levels of predation over their nondisked treatment counterparts (Table 7, Fig. 2). One possible explanation for this might be that the pine voles are attracted to the loosened soil in the disked areas because of easier tunneling. Pine vole tunneling, however, was observed in both disked and nondisked plots. Vole predation in the injection, girdling, and basal bark mid- and understory removal treatment plots were higher than in the control. Additionally, Tract P showed higher levels of vole predation than the other tracts. The increased numbers of oak seedlings that occurred in the disked plots compared to the nondisked plots, in the mid- and understory removal plots compared to their control, and finally in Tract P versus other tracts likely made these areas more attractive to foraging pine voles. Thus, pine voles appeared more attracted to, and predation on seedlings was higher in, areas where there were larger concentrations of oak seedlings, irrespective of particular treatments.

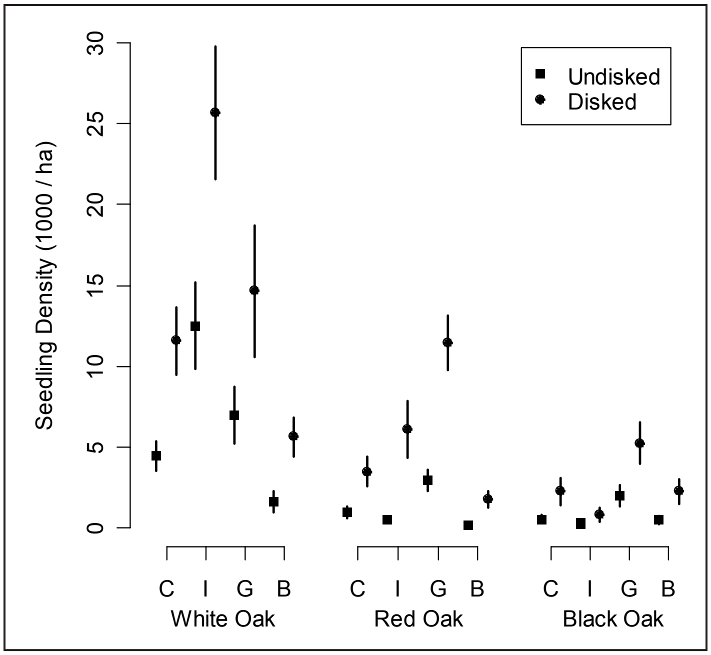

Figure 2.—Effects of disking and mid- and understory removal treatments on pine vole-induced mortality on a first-year cohort of oak seedlings growing in three mature oak stands in southern Indiana. Mid- and understory removal treatments were: no-removal treatment/control (C); herbicide injection (I); girdling and felling (G); and basal bark herbicide application (B).

Deer browsing on this cohort of oak seedlings was almost nonexistent. No deer browse-induced mortality was observed in the first growing season. Thus, it is unlikely that the large number of missing seedlings unaccounted for in the mortality estimates were pulled from the ground or clipped off at ground level by deer. Insect and disease damage was likewise very rare to nonexistent. Pine vole predation may account for the majority of unexplained oak seedling mortality in the first growing season. Vole herbivory on oak stems, and roots was recognized as early as 1907 (Lantz 1907). Little research has been published since then on vole–oak interactions. Pine voles were attracted to the dense vegetation that resulted from timber harvests that removed a substantial portion of the overstory (Perry and Thill 2005). Ostfeld and Canham (1993) studied the role of voles in woody plant dynamics in early successional habitats. Neither of these studies examines vole–oak seedling dynamics in the oak seedling establishment phase under a mature oak forest canopy.

CONCLUSIONS

Disking immediately following acorn dispersal in the fall greatly increased oak seedling establishment one growing season later. Increasing ground-level light by mid- and understory removal improved first-year oak seedling survival. Timely removal of these canopy layers is important to first year oak seedling survival and critical to the development of new seedlings into competitive oak regeneration. When workers use the ester formulation of triclopyr for basal bark applications or any potentially volatile forms of herbicide in mid- and understory removal operations, they should time the treatment to avoid air temperatures exceeding 28 to 30 °C, thus preventing significant first-year oak seedling damage. Pine voles have never been implicated in first-year oak seedling mortality in previous oak regeneration studies. Our study shows that this seedling predator may have substantial localized effects on first-year oak seedling survival. More investigation is needed to determine the extent of pine voles' impact on oak regeneration dynamics, both spatially and temporally.

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THE STATUS OF OAK AND HICKORY REGENERATION IN FORESTS OF VIRGINIA

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Abstract.—Evidence suggests that eastern U.S. forests dominated by oak (*Quercus* spp.) and hickory (*Carya* spp.) may be shifting to more maple- (*Acer* spp.) and mixed-species dominated forests. Data from the U.S. Forest Service Forest Inventory and Analysis program were used to describe the status of oak and hickory regeneration in medium- and large-diameter stands that showed no evidence of artificial regeneration or harvesting since the previous survey (5 to 10 years). Oak saplings (d.b.h. 2.5 cm but <12.7 cm) were tallied on 32 percent of plots measured and represented 10 percent of all saplings tallied. Hickory saplings occurred on 19 percent of plots measured and represented 5 percent of saplings tallied. In contrast, oak and hickory trees (d.b.h. ≥12.7 cm) occurred on 86 percent and 51 percent of plots, respectively. White oak (*Quercus alba* L.) and chestnut oak (*Q. prinus* L.) were the dominant oak saplings. Sapling-sized white and chestnut oaks occurred on 10 percent and 8 percent of plots, whereas tree-sized white and chestnut oaks occurred on 48 percent and 45 percent of plots, respectively. Density of chestnut oak saplings was less than one-half of that of trees (23 saplings ha^{-1} versus 58 trees ha^{-1}). Mockernut hickory (*Carya tomentosa* (Poir.) Nutt.) and pignut hickory (*C. glabra* [Mill.]) Sweet) were the most commonly tallied hickory saplings and both occurred on approximately 9 percent of plots. In contrast to the oaks and hickories, red maple (*Acer rubrum* L.) saplings occurred on 41 percent of plots. Given the status of regeneration of most oaks and hickories, it appears that these forests may be making a transition to a different species mix.

INTRODUCTION

The oak-hickory (*Quercus* spp.-*Carya* spp.) complex is the largest forest vegetation association in the eastern United States. Currently, it covers approximately 3,859,500 ha (60 percent) of all forest land in Virginia (Rose, in press). Chestnut oak (*Q. prinus* L.), at 3.4 m^2 ha^{-1}, is the dominant species across Virginia. White oak (*Quercus alba* L.), at 2.1 m^2 ha^{-1}, is the third most dominant species, and the second most dominant oak species (Rose and Rosson 2007). While oak is a major genus in forests of the eastern U.S., the loss of American chestnut (*Castanea dentata* [Marsh.]) Borkh.) may have contributed to an increase in the dominance of oak and hickory after 1900 (Keever 1953, Woods and Shanks 1959, McCormick and Platt 1980, Abrams 1992). Although oaks and hickories are still major overstory dominants, they are often under-represented in the understory (Stephenson 1986, McCarthy and Wistendahl 1988, Farrell and Ware 1991, Cole and Ware 1997, Abrams and Copenheaver 1999, Tift and Fajvan 1999, Copenheaver and others 2006, McEwan and Muller 2006). Additionally, several studies have reported a decrease over time in oaks or hickories, or both, and an increase in fire-intolerant and shade-tolerant species, especially in the understory (Christensen 1977, Rhoades 1992, Stephenson and Fortney 1998, Elliott and others 1999, Pierce and others 2006). This situation signals a potential transition from an oak and hickory species mix to more mesic shade-tolerant species. This shift in dominance is often attributed to the low shade tolerance of oaks and to the lack of disturbance, primarily from fire suppression (Burns and Honkala 1990, Abrams 1992). However, little or no benefit to oak has been reported from several prescribed burn studies (Wendel and Smith 1986, Hutchinson and others 2005, Blankenship and Arthur 2006). Notable among

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the potential replacement species are red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* Marsh.), and blackgum (*Nyssa sylvatica* L.) (Ross and others 1982, Abrams 1998, Pierce and others 2006). Whether these shade-tolerant, fire-sensitive species will assume a dominant overstory position in the future is uncertain. Some have speculated that oak may persist on xeric, nutrient-poor sites, even in the absence of fire, particularly in areas south and west of the northern hardwood forests (Orwig and Abrams 1994, Abrams and others 1997). If so, oak species adapted to these sites, such as chestnut oak and scarlet oak (*Q. coccinea* Muenchh.), may experience less successional pressure than oak species adapted to more mesic nutrient-rich sites, such as northern red oak (*Q. rubra* L.).

OBJECTIVES

Studies of vegetation composition are often limited in scale, and many times the selection of plot location is subjective and preferential. Preferential sampling emphasizes unique stands like old-growth forests or stands with unusual features, such as rare species. In contrast, this study utilized plots distributed systematically across Virginia. This approach allowed for the study of a wide range of stands across a variety of site and soil conditions and captured the most common stand conditions influencing vegetation across Virginia. The objective of this study was to describe the current regeneration status of oak and hickory species at the landscape scale across Virginia.

METHODS

This study was conducted in the state of Virginia, which has a total land area of Virginia is 10,255,000 ha. Approximately 62 percent of this total is forested (6,412,000 ha) (Rose 2007). The western portion of Virginia contains three mountainous physiographic regions, the Blue Ridge, the Ridge and Valley, and the Appalachian Plateau. To the east of these mountains is the Piedmont physiographic region, which ranges from rolling hills in the west to several nearly level basins in the east. The easternmost part of the state lies on the Coastal Plain, which extends inland approximately 200 km from the coast and is defined by the eastern Atlantic shoreline and the rolling and dissected area where it meets the Piedmont to the west (Fenneman 1938). The elevation in Virginia ranges from sea level to just over 1,737 m on Mt. Rogers in the George Washington and Jefferson National Forest.

Data for this study came from the forest survey conducted in Virginia between 1997 and 2001 by the U.S. Forest Service, Southern Research Station, Forest Inventory and Analysis (FIA) program. Surveys such as this have been conducted since the early 1930s, under the direction of several legislative acts. The survey mission originally was to estimate forest area, timber volume, growth, removals, and mortality, but it has since been broadened in scope to address other contemporary forest issues.

A hexagonal grid system was used to establish sample plots and derive forest statistics (USDA 2004). Within each 2430-ha hexagon, a randomly located sample plot was measured to determine individual tree and forest stand parameters. On each plot trees ≥12.7 cm diameter at breast height (d.b.h.) were sampled on four subplots, each with a radius of 7.3 m, spaced 37 m apart. Together these four subplots made up a sample plot with a sample area of 0.07 ha. Saplings (2.5 cm - 12.6 cm d.b.h.) were measured on microplots with a radius of 2.1 m nested within each subplot. The total sample area of the four microplots was 0.005 ha.

The plot population for this study was derived by means of a post-stratified plot selection based upon the following criteria: (1) each plot was internally homogeneous regarding stand size and forest type; (2) the plots were not artificially regenerated; (3) the plots showed no evidence of cutting since the previous survey (5 to 10 years); and (4) the plots were classified as either medium-diameter or large-diameter stands based on stocking. Large diameter trees are >27.7 cm d.b.h. for hardwoods and >22.6 cm d.b.h. for softwoods. Medium-diameter trees are 12.7 - 27.7 cm d.b.h. for hardwoods and 12.7 - 22.6 cm d.b.h. for softwoods. Out of 3,037 forested plots, 1,164 met these requirements.

Density for genus and species was calculated for all plots. The heterogenous distribution of trees across the landscape, with many plots having a value of zero for most species, may result in a standard deviation that equals, or exceeds, the mean. Relative density (density of species [or genus]/total density [in stems ha^{-1}] x 100) was also calculated for each genus and species for all plots. Taxonomic nomenclature follows Little (1979). FIA includes red hickory (*Carya ovalis* (Wangenh.) Sarg.) with pignut hickory (*Carya glabra* (Mill.) Sweet).

RESULTS

Sapling-size oaks (≥2.5 cm d.b.h., but <12.7 cm) occurred on 30 percent of plots and represented 10 percent of all saplings tallied. Hickory saplings were present on 18 percent of plots and represented 5 percent of saplings tallied. In contrast, oak and hickory trees (d.b.h. ≥12.7 cm) were found on 86 percent and 51 percent of plots, respectively, and accounted for 36 percent and 6 percent of trees, respectively. Sapling-size hickories were present on only 26 percent of plots where tree-size hickories occurred. Likewise, 33 percent of plots with tree-size oaks had sapling-size oaks. Conversely, hickory saplings occurred on 9 percent of plots that did not have hickory trees, and oak saplings occurred on 13 percent of plots that did not have oak trees.

Maple (*Acer* spp.) and tupelo (*Nyssa* spp.) were on the most plots and represented the most saplings tallied. Sapling-size maples occurred on 49 percent of plots and accounted for 22 percent of saplings tallied. Tree-size maples occurred on 71 percent of plots and represented 12 percent of trees. Tupelo saplings occurred on 31 percent of plots and accounted for 12 percent of saplings tallied. Trees of this genus occurred on 35 percent of plots and represented 3 percent of trees.

Sapling-size oaks that occurred on at least 5 percent of plots were white oak (10 percent of plots), chestnut oak (8 percent), and northern red oak (5 percent) (table 1). In contrast, trees of these three oaks occurred on 48 percent, 45 percent, and 42 percent of plots, respectively. Mockernut hickory (Carya tomentosa (Poir.) Nutt.) and pignut hickory were the most commonly tallied sapling-size hickories and each occurred on approximately 9 percent of plots. Trees of these two species occurred on about one-third of the plots. The most frequently occurring sapling-size species were red maple, blackgum, and yellow poplar (*Liriodendron tulipifera* L.).

Although the density of tree-size oak species exceeded that of hickories, saplings of mockernut hickory and pignut hickory had higher densities than saplings of any oak species, with the exception of white oak (Table 2). In contrast to chestnut oak trees, density of chestnut oak saplings was higher in oak-pine stands (32 stems ha^{-1}) than in oak-hickory stands (24 stems ha^{-1}) (Table 3). Mockernut hickory was another species where sapling density was higher in oak-pine stands (33 stems ha^{-1}) than in oak-hickory stands (28 stems ha^{-1}). This situation was also true for several other species; however, in some cases, including white oak and scarlet oak, the density of trees was also higher in oak-pine than in oak-hickory stands. Density of chestnut oak saplings was less than one-half that of trees (22 trees ha^{-1} versus 58 trees ha^{-1}). White oak

Table 1.—Frequency of individual sapling and tree species, Virginia, number of plots=1,164. The 33,203 tree-sized stems included 94 species and the 6,475 sapling-sized stems included 76 species; only the top 15 species (for tree basal area) are included.

		Frequency			
Scientific name	Common name	Saplings[1]		Trees[2]	
		no.	%	no.	%
Acer rubrum	Red maple	483	41.5	764	65.6
Carya glabra	Pignut hickory	99	8.5	355	30.5
C. tomentosa	Mockernut hickory	110	9.5	341	29.3
Fagus grandifolia	American beech	90	7.7	159	13.7
Liquidambar styraciflua	Sweetgum	119	10.2	225	19.3
Liriodendron tulipifera	Yellow-poplar	124	10.7	569	48.9
Nyssa sylvatica	Blackgum	347	29.8	381	32.7
Pinus strobus	E. white pine	71	6.1	145	12.5
P. taeda	Loblolly pine	19	1.6	142	12.2
P. virginiana	Virginia pine	48	4.1	281	24.1
Quercus alba	White oak	119	10.2	562	48.3
Q. coccinea	Scarlet oak	48	4.1	369	31.7
Q. prinus	Chestnut oak	92	7.9	525	45.1
Q. rubra	Northern red oak	63	5.4	486	41.8
Q. velutina	Black oak	45	3.9	388	33.3

[1] d.b.h. ≥2.5 cm but <12.7 cm
[2] d.b.h. ≥12.7 cm

Table 2.—Average density and relative density of individual sapling and tree species (across all plots), Virginia. Values in parentheses are the standard deviation. The 33,203 tree-sized stems included 94 species and the 6,475 sapling-sized stems included 76 species; only the top 15 species (for tree basal area) are included.

	Saplings[1]		Trees[2]	
Species	Density	Relative Density	Density	Relative Density
	stems ha^{-1}	%	stems ha^{-1}	%
Red maple	182.7 (328.1)	16.3	44.6 (60.6)	10.6
Pignut hickory	22.3 (89.4)	2.6	10.5 (22.1)	2.8
Mockernut hickory	24.7 (89.6)	2.3	10.6 (23.7)	2.8
American beech	29.4 (132.8)	2.7	6.6 (23.1)	1.6
Sweetgum	42.5 (183.9)	3.2	14.8 (44.8)	3.2
Yellow-poplar	40.7 (181.3)	3.2	37.4 (61.6)	9.4
Blackgum	118.7 (253.0)	11.8	10.6 (25.2)	2.6
E. white pine	21.5 (105.0)	2.1	8.1 (32.8)	1.8
Loblolly pine	8.6 (101.3)	0.4	16.6 (72.4)	3.0
Virginia pine	17.7 (145.8)	1.1	22.5 (76.5)	4.3
White oak	29.8 (108.2)	2.2	33.6 (55.0)	8.2
Scarlet oak	10.0 (56.9)	1.0	19.1 (43.8)	4.3
Chestnut oak	21.8 (90.1)	2.3	57.7 (95.6)	13.5
Northern red oak	11.9 (54.4)	1.4	18.1 (38.3)	4.4
Black oak	8.1 (42.3)	0.7	12.4 (26.1)	3.0

[1] d.b.h. ≥2.5 cm but <12.7 cm
[2] d.b.h. ≥12.7 cm

Table 3.—Average density of individual sapling and tree species by forest-type group, Virginia. The 33,203 tree-sized stems included 94 species and the 6,475 sapling-sized stems included 76 species; only the top 15 species (for tree basal area) are included.

	Forest-type group[1]					
	Oak-Hickory (n = 856)		Oak-Pine (n = 146)		Other[2] (n = 162)	
Species	Saplings[3]	Trees[4]	Saplings	Trees	Saplings	Trees
	stems ha^{-1}					
Red maple	181.6	43.5	228.9	39.8	219.2	54.6
Pignut hickory	26.3	12.9	21.2	5.0	9.1	2.9
Mockernut hickory	28.1	12.7	33.1	7.3	6.5	2.9
American beech	33.8	7.7	21.2	2.7	24.8	4.5
Sweetgum	23.0	10.5	127.0	24.7	90.0	28.8
Yellow-poplar	46.4	43.2	17.2	23.2	48.3	19.8
Blackgum	135.5	10.9	103.2	11.6	86.1	7.8
E. white pine	14.0	3.5	80.7	30.4	15.7	12.7
Loblolly pine	1.6	2.7	22.5	34.8	39.1	73.2
Virginia pine	9.5	7.6	22.5	51.7	67.8	74.5
White oak	27.0	35.7	62.2	46.2	26.1	10.7
Scarlet oak	9.0	19.2	21.2	27.3	9.1	11.2
Chestnut oak	23.9	67.2	31.8	49.5	9.1	15.0
Northern red oak	15.8	22.1	1.3	9.1	5.2	5.4
Black oak	6.5	14.0	13.2	14.0	15.7	2.9

[1] Forest-type groups are similar in concept to associations as defined by Braun (1950).
[2] Other includes maple-beech-birch, bottomland-hardwoods, loblolly-shortleaf pine, and white-red-jack pine forest-type groups.
[3] d.b.h. ≥2.5 cm but <12.7 cm
[4] d.b.h. ≥12.7 cm

was the only oak species whose sapling-to-tree ratio approached 1 to 1 (Table 2). Pignut and mockernut hickory both had sapling-to-tree ratios of approximately 2 to 1. Blackgum and red maple ratios were 12 to 1 and 4 to 1, respectively.

Sapling-size chestnut oak, white oak, mockernut hickory, and pignut hickory all had relative densities ≥15 percent on 6 percent of plots. Trees of these four species had relative densities ≥15 percent on 30 percent, 20 percent, 5 percent, and 5 percent, respectively. Northern red oak saplings reached a relative density ≥15 percent on 4 percent of plots and both black oak and scarlet oak had relative densities ≥15 percent on only 2 percent of plots. Other potential overstory sapling-size species that had relative densities ≥15 percent were red maple (36 percent of plots), blackgum (24 percent), and yellow-poplar (8 percent). Relative densities of trees of these three species were ≥ 15 percent on 26 percent of plots, 4 percent, and 23 percent, respectively.

DISCUSSION

At the landscape scale across Virginia, the regeneration potential of oak species and, to a lesser degree, hickory species appears low compared to several other species. The canopy tree species with the highest sapling densities tended to be the mesic shade-tolerant ones, in particular red maple and blackgum. It is likely that without disturbance these species will increase in abundance and oak and hickory species will decrease. However, there is some evidence that a single disturbance on some sites may not be sufficient to increase the recruitment of oak and hickory (Clark and others 2007). Studies from the mountains and the Piedmont of Virginia have also found high amounts of oak in the overstory, but very little in the understory (Farrell and Ware 1991, Abrams and Copenheaver 1999, Copenheaver and others 2006). In addition, studies from West Virginia, Kentucky, and Indiana also found that stands dominated by oaks and hickories tended to have different species in the understory (Tift and Fajvan 1999, McEwan and Muller 2006, Pierce and others 2006). This study found that most oak and hickory species occurred on far fewer plots in the sapling size class than the tree size class. In contrast, Cole and Ware (1997) found that many of the oak and hickory species of the Piedmont of Virginia were present on most plots in the small tree and sapling size class where they also occurred in the overstory.

The higher density of some oak saplings in oak-pine stands may be due to recent disturbance, or may be indicative of drier sites with relatively open canopies that allow sufficient light penetration for successful oak regeneration. In comparison, the density of white oak saplings was greater in stands dominated by Virginia pine (*Pinus virginiana* Lam.) than white oak-yellow-poplar stands in a study from the Piedmont and Coastal Plain of Virginia (Orwig and Abrams 1994). Additionally, southern red oak (*Q. falcata* Michx.) and black oak (*Q. velutina* Lam.) sapling densities were higher in the Virginia pine stands than in either the white oak-yellow-poplar or the white oak-scarlet oak forest groups. This case also held true for seedlings of southern red oak; however, black oak seedlings were not present in any of the forest groups (Orwig and Abrams 1994).

The dominance of red maple and/or blackgum in the sapling layer has been documented by many researchers (Ross and others 1982, Abrams and Downs 1990, Farrell and Ware 1991, Orwig and Abrams 1994, Cole and Ware 1997, Tift and Fajvan 1999). This dominance, however, has been found to vary along topographic moisture gradients. Ross and others (1982) found that for trees less than 7 years old, red maple outnumbered chestnut oak on mesic sites, while blackgum outnumbered chestnut oak on xeric sites. Whether red maple will become a canopy dominant is uncertain. Researchers have been noting relatively high or increasing occurrences for decades (Keever 1953, Woods and Shanks 1959, Stephenson 1974). However, the species has not yet assumed the overstory dominance that might be assumed given the high importance reported in under- and mid-story layers. Recruitment of red maple into the overstory nonetheless has been reported from a few studies (Rhoades 1992, Elliott and others 1999, Blankenship and Arthur 2006, McEwan and Muller 2006). Across all plots in this study, red maple trees ranked fourth in basal area, and second in density. This presence seems to support the idea that there is potential for red maple to assume a more dominant position in the forests of the eastern U.S.

Low numbers of oak saplings do not necessarily translate into a lack of future dominance by oaks (Abrams and other 1998). Reproduction of some species may be periodic (i.e., regenerating at irregular intervals) rather than continuously (Whittaker 1956). Decelerated height growth of maple over time, a relatively shorter life span (150 years for maple versus 200 to 500 years for several oaks and hickories), as well as high understory mortality of blackgum may limit the ability of these species to assume and maintain canopy dominance (Christensen 1977, Burns and Honkala 1990, Abrams 1992, Cole and Ware 1997).

Hickory saplings were more abundant than hickory trees, which is often true for many species. The density of mockernut hickory and pignut hickory saplings equaled or exceeded that of most other oak species, which was unexpected. Other studies from the northern Piedmont region of Virginia also found that hickory was more prevalent than oak in the understory, although oak dominate species in the overstory (Farrell and Ware 1991, Abrams and Copenheaver 1999). Whether hickory will become a dominant component of the overstory in the future is uncertain. In 1953, Keever predicted a substantial hickory component would exist in the former oak-chestnut forests in the southern Blue Ridge Mountains. McCormick and Platt (1980) confirmed that hickory had maintained a co-dominant position, and was the leading dominant in some stands in the same area. Further south, in the central Piedmont of Virginia, one study found that hickory was present, although less prevalent than in the northern Piedmont (Cole and Ware 1997). Studies from the Coastal Plain of Virginia found either little or no hickory in the understory or overstory (Monette and Ware 1983, Abrams and Black 2000). While the present study did not take into account spatial variability, it is likely that sapling densities of hickory were highest in the northern Piedmont region of Virginia. A related study found that hickory trees obtained their highest importance values in this area (Rose and Rosson 2007), perhaps in part because of the association of hickory species with soils of high Ca and high Mg as are found in the northern Piedmont region of Virginia (Farrell and Ware 1991).

In addition to spatial variability, some oak and hickory species tend to be correlated with topography (Racine 1971, Stephenson 1974, Ross and others 1982, McCarthy and others 1984, McCarthy and Wistendahl 1988, Collins and Carson 2004, Copenheaver and others 2006). Future studies that consider these factors will further clarify the status of regeneration of oak and hickory. Additionally, follow-up work that includes seedlings will provide insight into the future composition of these forests. Although only data from permanent plots without evidence of management in the past 10+ years were used in the analyses, natural disturbance and land use history may have had an effect on the status of regeneration of the species investigated in this study.

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ANALYSIS OF RIPARIAN AFFORESTATION METHODS IN THE MISSOURI OZARKS

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Abstract.—We evaluated the first-year survival and growth of 13 bottomland species in several different management treatments replicated at three sites in the Missouri Ozarks. Treatments were: 1) Roundup® site preparation only; and Roundup® site preparation plus a: 2) growing season application of Poast Plus® (a grass-selective herbicide); 3) redtop cover-crop; 4) ladino clover cover-crop; or a 5) Virginia wild rye cover-crop. We also compared the resulting structure and composition of competing ground flora at ground level and at 0.625 meters (average tree seedling height). Seedling survival was lowest in the Virginia wild rye treatment (83 percent) and highest in the redtop treatment (91 percent). Green ash (98 percent) and swamp white oak (97 percent) had the highest survival while eastern cottonwood (43 percent) and pecan (71 percent) had the lowest. Height growth increment by treatment was greater across all cover-crop treatments than in the herbicide-only treatments. The highest increment was redtop (9.7 cm) and the lowest was Roundup®-only (3.9 cm). Height growth by species was highest for swamp white oak (10.5 cm) and green ash (10.1 cm), whereas hackberry (-8.1 cm) and pecan (-3.9 cm) had negative growth as a result of herbivory or shoot dieback. Resulting ground flora densities were consistently lowest in the Poast Plus® treatments and highest in the Roundup®-only and rye treatments.

INTRODUCTION

In Missouri, mature hardwood forests were once abundant in floodplains of the Ozark region (Nigh and others 1992). Large-scale conversion of Ozark bottomland forests to agriculture began in the early 1800s (Jacobson and Primm 1994) and continued to be a common practice into the middle part of the 20th century. Loss of riparian forests in the Ozarks has resulted in accelerated bank erosion, channel destabilization, increases in stream temperature, and degradation of aquatic and riparian fish and wildlife habitat (Roell 1994). Overall, greater than 85 percent of the original floodplain forests in Missouri have been converted to some other use (Dey and others 2001). Currently, there is considerable interest in replanting hardwoods in old fields and former pastures along riparian corridors in Missouri, and throughout the Central Hardwood Forest Region.

Recently, a number of federal and statewide efforts to re-establish bottomland hardwoods have largely met with poor or mixed success (Dey and others 2001, Kabrick and Dey 2001, Stanturf and others 2001, Dugger and others 2004, Kabrick and others 2007). Initial stages of such restoration projects are important and will subsequently direct successful hardwood establishment. Important considerations include: species appropriateness to site, seedling stock type, wildlife damage, tree planting technique, and groundcover management. Overall, methods for restoring bottomland hardwoods have not yet been fully developed.

Most riparian afforestation projects have focused on planting hard-mast-producing species, such as oaks (*Quercus* spp. L.), pecan (*Carya illinoinensis* (Wangenh.) K. Koch), and black walnut (*Juglans nigra* L.). Less

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commercially valuable light-seeded species are often omitted, in part because of the assumption that these species will naturally establish themselves. However, Stanturf and others (2000) suggested that relying on the natural establishment of light-seeded, wind-dispersed species into agricultural forest conversions may be impractical or unsuccessful. Consequently, interest is increasing in including these species in bottomland plantings (Lockhart and others, in review). However, there is little information about the artificial regeneration of many of the light-seeded species.

Vegetation management is an extremely important part of any afforestation project, and only second to species-site considerations (Van Sambeek and Garrett 2004). Groundcover management can be used to reduce competition for water and nutrients and to minimize labor and equipment costs. To gain the greatest positive effects on plantation success, vegetation management should be conducted during the first 1 to 3 years following planting (Miller 1993). Types of management include mechanical or chemical control of competing vegetation, and planting cover-crops. Mechanical control includes mowing, which is a common practice managers use to facilitate chemical treatments, and to help locate newly planted trees. However, mowing itself is ineffective for controlling competing vegetation for improved seedling survival and growth (Van Sambeek and Garrett 2004). Chemical methods include application of a variety of pre- and post-emergent herbicides, including those that can be applied over trees, such as grass-selective herbicides. Cover-crops have also been shown to be effective in suppressing competing vegetation, leading to improved tree survival and growth (Van Sambeek and Garrett 2004). In addition, cover-crops may be used to conserve soil and to improve water quality (Dey and others, in review). Specifically, grass species such as redtop (*Agrostis giantea* Roth) have been successfully established in bottomland hardwood plantings in Missouri with a minimal investment, high success, and little follow-up management (Dey and others 2003). Other options for cover-crops include legumes with nitrogen-fixing properties, such as clovers (*Trifolium* spp. L.). Legumes have often proven more successful in hardwood tree plantings than both grasses and resident vegetation (Van Sambeek and Garrett 2004). To date, there has been little research in using native species for this type of work. Many have speculated that Virginia wild rye (*Elymus virginicus* L.) might be a suitable option because of its general distribution and growth habit. In Missouri, Virginia wild rye grows in a variety of settings, from intact riparian communities, to glades and old fields (Yatskievych 1999).

OBJECTIVES

Our objective was to compare the effect of two herbicides and three cover-crop management practices on 13 species of seedlings to identify successful afforestation methods for use in riparian ecosystems of the Ozark Highlands.

STUDY AREAS

Three replicate sites were included in this study. Study locations were selected based upon their geographic distribution, placement within watershed, current and former land condition, and land ownership type. All sites were located within the Ozark Highlands Ecological Section, as described by Nigh and Shroeder (2002) (Fig. 1). Study areas were confined to this region because of the distinctive topographical characteristics and area-specific land management questions occurring here. Waterways within this region flow through a highly dissected, unglaciated landscape. Streams adjacent to Ozark riparia are mostly spring-fed and carry little suspended sediment (Nigh and Schroeder 2002). Here, drainage systems are characterized as "open," with a brief water residence time. Compared to surrounding regions, fluvial soils are coarsely grained and droughty. Stream systems of this study were 2nd and 4th order (Strahler 1957). Each research plot was located on well developed and relatively stable point-bar floodplains subject to

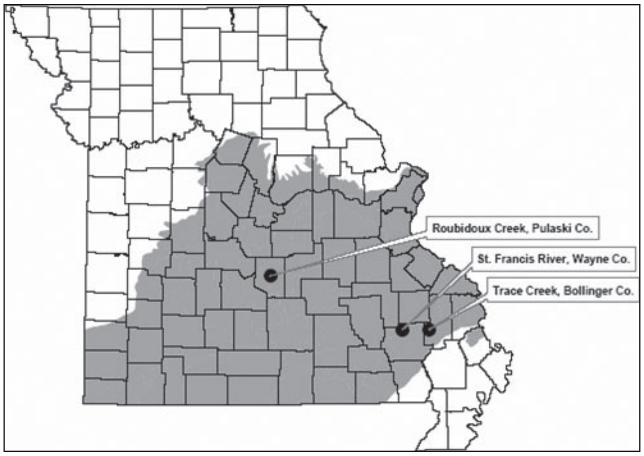

Figure 1.—Study site locations in Missouri. Ozark Ecological Section is shaded in gray (Nigh and Schroeder 2002).

Table 1.—Soils and associated physical characteristics of each study site

Study site	Soil series	Landform type	Drainage class	Taxonomic class
St. Francis River	Bucklick	footslope	well	Fine, mixed, active, mesic Typic Hapludalfs
	Crider	footslope	well	Fine-silty, mixed, active, mesic Typic Paleudalfs
	Fourche	terrace	moderately well	Fine-silty, mixed, active, mesic Glossaquic Paleudalfs
	Freeburg	terrace	somewhat poorly	Fine-silty, mixed, superactive, mesic Aquic Hapludalfs
	Raccoon	terrace	poorly	Fine-silty, mixed, superactive, mesic Typic Endoaqualfs
	Secesh	terrace	moderately well	Fine-loamy, siliceous, active, mesic Ultic Hapludalfs
Trace Creek	Razort	floodplain	well	Fine or coarse-loamy, mixed, active, mesic Mollic Hapludalfs
	Secesh	floodplain	well	Fine-loamy, siliceous, active, mesic Ultic Hapludalfs
	Tilk	floodplain	well	Loamy-skeletal, siliceous, active, mesic Ultic Hapludalfs
Roubidoux Creek	Kickapoo	floodplain	well	Coarse-loamy, mixed, superactive, nonacid, mesic Typic Udifluvents
	Sandbur	floodplain	somewhat excessively	Coarse-loamy, siliceous, superactive, nonacid, mesic Mollic Udifluvents
	Relfe	floodplain	excessively	Sandy-skeletal, siliceous, mesic Mollic Udifluvents

occasional to infrequent flooding. Prior to site establishment, Missouri Department of Natural Resources soil scientists mapped the soils at each site at a resolution of 1:2,000 (Table 1). Sites were generally located on floodplain or terrace landforms. Soil orders were either Entisols or Alfisols and ranged from excessively well drained with sandy-skeletal texture, to somewhat poorly drained with fine-silty texture. Planting area at each site ranged from 1.5 to 2 hectares in size.

Table 2.—Species, number of seedlings, and mean initial height of bare-root seedlings (or cuttings of cottonwood) used in this study. Initial measurements were not collected for eastern cottonwood. Fisher's least significant difference = 2 cm.

Common name	Latin name	n	Initial height (cm)
Swamp white oak	*Quercus bicolor*	212	34
Northern red oak	*Q. rubra*	374	47
Pin oak	*Q. palustris*	204	48
Shumard oak	*Q. shumardii*	373	49
Bur oak	*Q. macrocarpa*	378	43
White oak	*Q. alba*	367	35
Black walnut	*Juglans nigra*	430	45
Pecan	*Carya illinoinensis*	367	39
White ash	*Fraxinus americana*	363	55
Green ash	*F. pennsylvanica*	383	55
American sycamore	*Platanus occidentalis*	375	78
Hackberry	*Celtis occidentalis*	364	51
Eastern cottonwood	*Populus deltoides*	311	--

METHODS

We evaluated first-year growth and survival response of 13 native tree species commonly used in bottomland plantings in the Ozark region (Table 2). Bare-root seedling stocks were used, which are the most widely-available and commonly used stock type in the region (Dey and others, in review). All seedlings were planted in March or April of 2006. Seedlings were purchased from the George O. White State Tree Nursery near Licking, MO. All seedlings were either 1-0 or 2-0 stock, with the exception of eastern cottonwood (*Populus deltoides* Batr. ex Marsh.), which were planted as 30-cm cuttings. Prior to planting, seedlings of all species were randomly packaged together to ensure random placement in the field.

All planting locations were initially sprayed with a 2 percent solution of Roundup® (41 percent a.i.) to eliminate pre-existing cool-season pasture grasses and other agricultural weeds. Treatments were: 1) Roundup® site preparation only; and Roundup® site preparation plus a 2) single growing season application of a grass-selective post-emergent herbicide, Poast Plus® (13 percent sethoxydim a.i.); 3) redtop cover-crop; 4) ladino clover (*Trifolium repens* var. *giganteum* L.) cover-crop with annual wheat (*Triticum aestivum* L.) nurse-crop; and 5) Virginia wild rye cover-crop with a Korean lespedeza (*Kummerowia stipulacea* [Maxim.] Makino) nurse-crop. Following the initial Roundup® application, fields receiving the three cover-crop treatments (i.e., redtop, clover, and rye treatments) were disked to a depth of 3 inches. Seed was then broadcast with either a hand-spreader or a PTO-powered tractor-mounted seeder directly before tree planting in March or April. Each treatment was planted separately at the following seed mixtures and rates: redtop at 11.1 kg per ha, ladino clover at 4.5 kg per ha, annual wheat at 174 L per ha, Virginia wild rye at 17.8 kg per ha, and Korean lespedeza at 8.9 kg per ha. Following seeding, a section of chain-link fence was dragged behind an all-terrain vehicle to maximize seed-soil contact. The "Poast Plus®" treatment was left idle until the target grass species were actively growing. The "Roundup®-only" treatment areas were left idle for the remainder of the study.

Following cover-crop seeding, tree seedlings were planted during the same day using a tree planter. A minimum of 20 seedlings per species per treatment were planted (Table 2), for a total of 4,501 seedlings. Planting spacing was somewhat dependent upon site area, but was generally 3 m x 3 m. A work crew followed the tree planter and replanted any poorly planted trees as needed. Following planting, initial height and diameter data were collected. All seedlings were remeasured in November 2006 at the completion of the first growing season.

Ground flora was surveyed during peak vegetative productivity of the growing season (i.e., middle July - early August) to quantify competing plant composition, abundance, and structure within each site and treatment type. Eighty 1-m^2 sample quadrates per hectare were randomly assigned to each treatment. Quadrats were aligned prior to field entry using geographic information systems software with aerial photographs and the previously collected soils data. At each quadrat, percent cover by species was tallied for any species comprising a minimum of 1 percent of the quadrat area, and all data recorded to the nearest percent. Each species was tallied regardless of its vertical placement within the quadrat. Therefore, it was possible that with vertical layering of vegetation, the sum of all species together could equal more than 100 percent. These data were used to quantify the vegetation competing for below-ground resources (e.g., water, nutrients, rooting space). In addition to quadrat (i.e., ground-level) data, information was recorded for foliar density by height class using a 2.5-m-tall by 0.3-m-wide profile board, with alternating black and white painted bands at each 0.25-m interval (Nudds 1977). These data were collected at 40 plots per hectare. At each plot, the profile board was oriented along the outside edge of the 1-m^2 quadrate frames used for the ground level sampling. Based on a specified azimuth, a logger's tape was used to establish a sampling point at a distance of 15 m. The amount of vegetation obscuring each 0.25-m interval on the profile board was estimated to the nearest percent for each plot. Observers ensured that their line-of-sight coincided directly with the height interval being measured.

We compared seedling survival and growth using analysis of variance (ANOVA) in a split-plot design, with the five groundcover treatments as the whole-plots, and the 13 species within treatments as the split-plots. The error term used was site (i.e., block) and was considered a random effect. Ground flora data (i.e., ground-level and foliar density by height class) were analyzed as an ANOVA randomized complete block design with percent cover as the response variable. Each site was one block. For significant effects (α = 0.05), we used the Fisher's least significant difference using the least squares means for all mean separations.

RESULTS

Seedling survival was more than 87 percent for all treatments. However, there were differences among treatments (p = 0.03, Fig. 2). Seedling survival in the rye cover-crop (83 percent) was lower than seedling survival for both redtop cover-crop (91 percent) and Poast Plus® (89 percent). The Roundup®-only treatment and clover cover-crop were in the middle.

Survival differed significantly among species (p <0.01, Fig. 2). Green ash survival exceeded 98 percent, surpassing pecan, sycamore, and cottonwood, which had the lowest survival. White oak and pin oak survival was approximately 90 percent. White ash, hackberry, black walnut, swamp white oak, northern red oak, Shumard oak, and bur oak all exhibited similar survival rates, between 94 and 96 percent.

Vegetation management treatment significantly influenced seedling height growth increment (p <0.01, Fig. 3). Seedlings grown in a cover-crop of either redtop, clover, or rye performed better than those grown

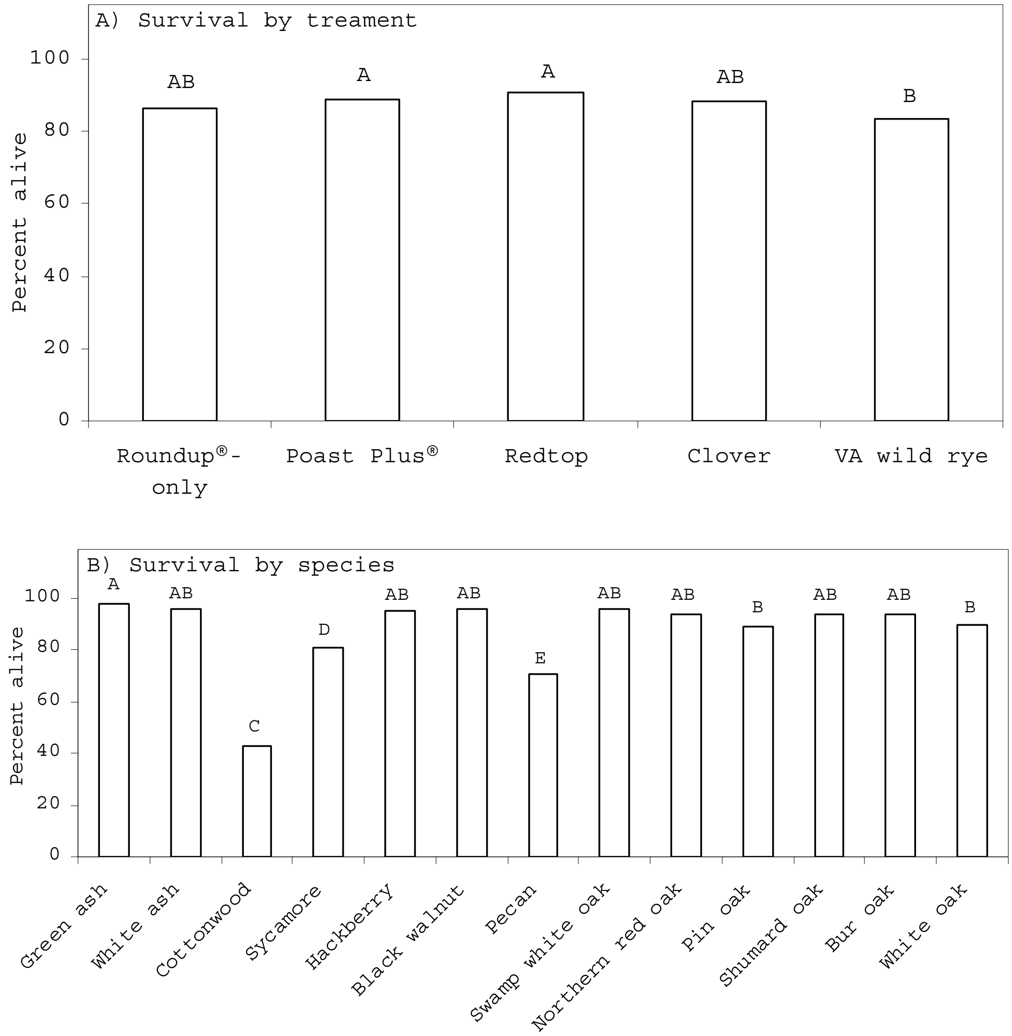

Figure 2.—Mean survival by (A) treatment (all species) and (B) species (all treatments). Letters above bars indicate statistical significance using Fisher's least significant difference for mean separations (α = 0.05).

with Roundup® only. Seedling growth increment in the Poast Plus® treatment was not significantly different from the Roundup®-only treatment. Overall, redtop nominally had the highest average growth of 9.7 cm, while the Roundup®-only treatment had the lowest, at 3.9 cm.

Height growth varied greatly among species ($p < 0.01$, Fig. 3). Eastern cottonwood had the highest average growth at 49.1 cm, which was much greater than all other species. Height growth of green ash and swamp white oak was greater than sycamore, hackberry, black walnut, pecan, Shumard oak, and bur oak. Hackberry and pecan each had negative growth, resulting from herbivory or shoot dieback. White ash, northern red oak, pin oak, and white oak all had similar height growth patterns, and were lower than green ash and swamp white oak.

The treatment effects for ground flora densities in both the foliar density by height class and ground level were highly significant ($p < 0.01$, Fig. 4). For foliar density by height class, we included only the 0.625-m interval, since this represented the average height of seedling foliage and the level at which a seedling's ability to capture light for production of photosynthate could be inhibited. For treatment effects of ground

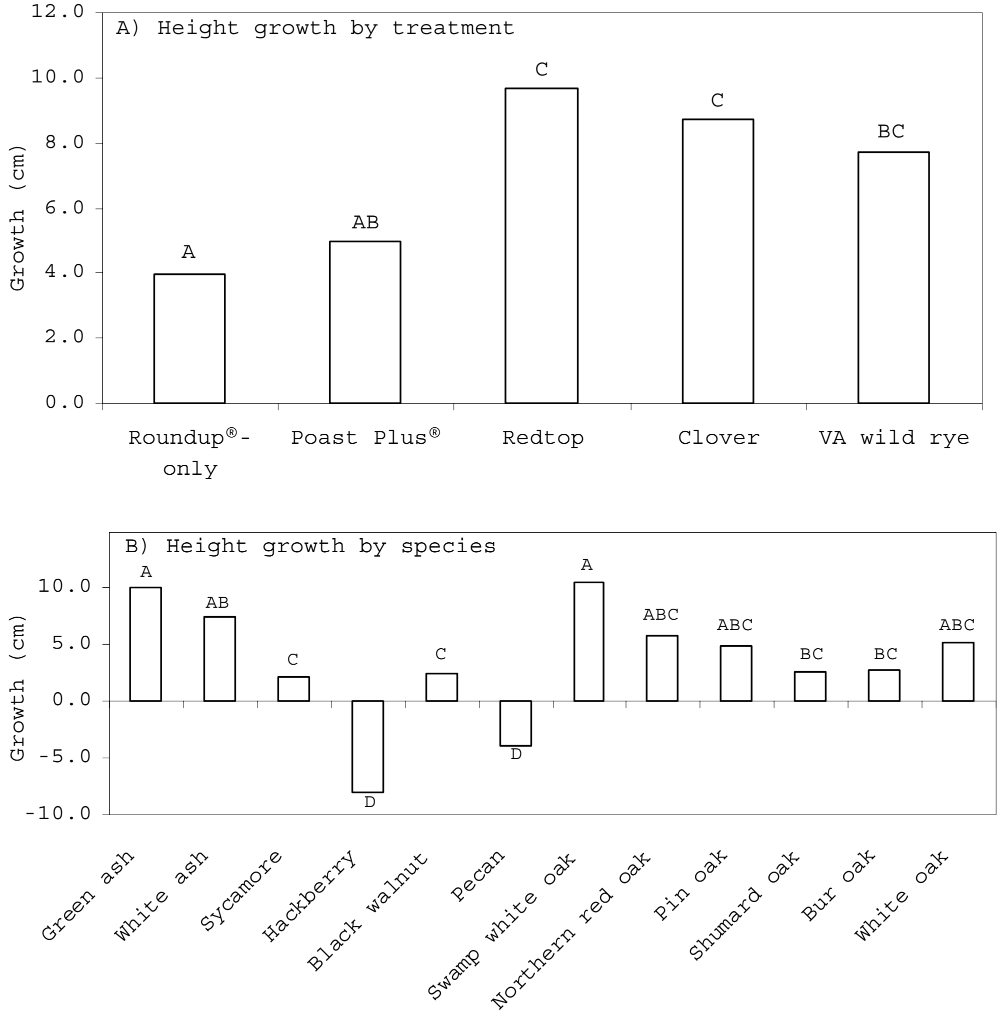

Figure 3.—Mean height growth by (A) treatment (all species) and (B) species (all treatments). Average height growth of cottonwood was 49.1 cm, and was omitted in order to key in on other species. Letters above bars indicate statistical significance using Fisher's least significant difference for mean separations (α = 0.05).

flora density at 0.625 m, Poast Plus® was significantly lower than all other treatments (49 percent). Foliar densities for the other treatments were similar, ranging between 84 and 95 percent. At the ground level, the highest density was in the rye cover-crop (exceeding 100 percent), for greater than both Poast Plus® and clover, each of which were lower than 75 percent. Roundup®-only and redtop fell in the middle, both having above 90-percent cover.

DISCUSSION

In Missouri, it is common for first-year seedling survival rates to be high. However, our study showed significant seedling survival differences among treatments. Rye had lower seedling survival than redtop and Poast Plus® at the end of the first growing season (Fig. 2) probably related to unsuccessful rye establishment. Although it was planted at a high seeding rate, the rye was nearly absent on all sites, leading to elevated competing ground flora densities (Fig. 4). During data collection, crews were instructed to specifically look for rye germinants, but few were found. This could have been a result of planting methodology, poor seed quality, or inadequate seed source. In addition, many native grasses can often take two to several years to establish (Launchbaugh 1976), which may be the case here. For surviving

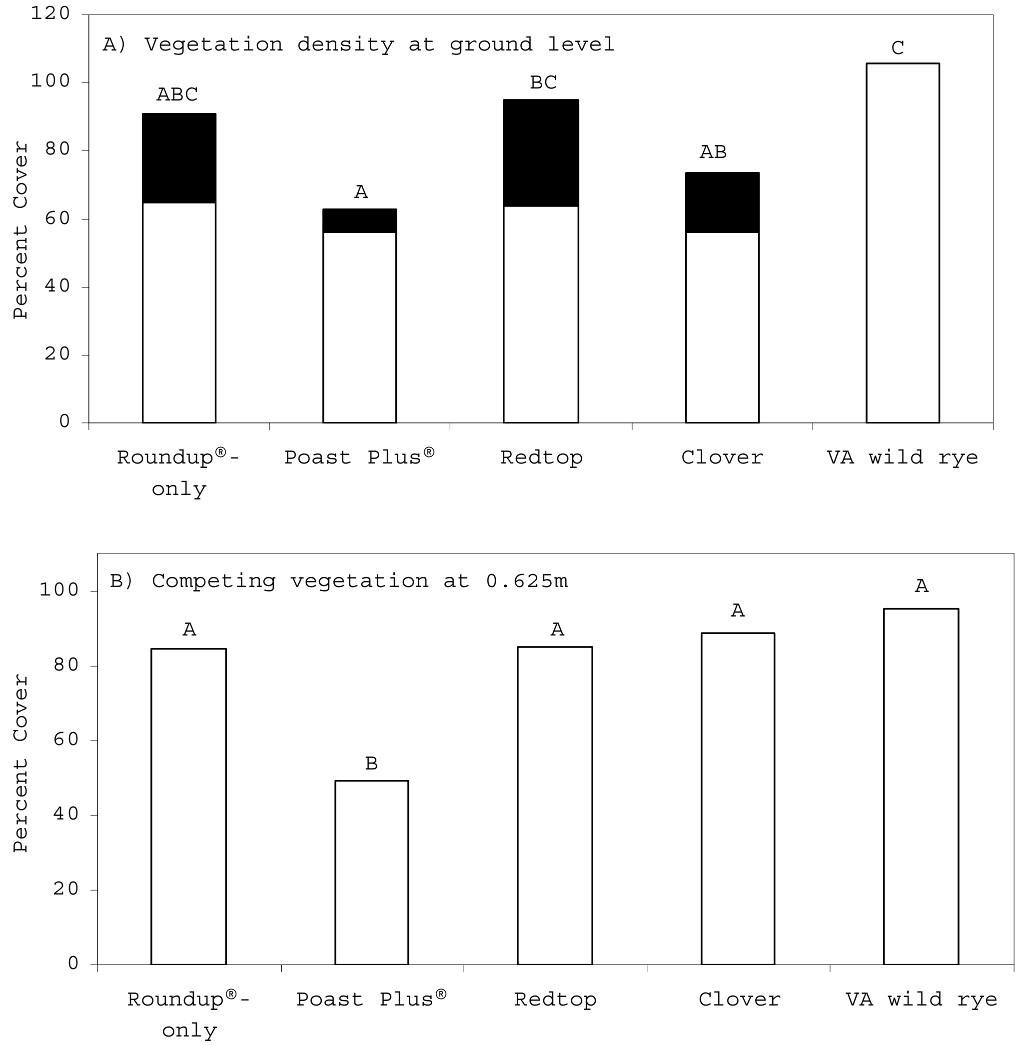

Figure 4.-Mean ground flora density by treatment. In graph A, filled portion of the bar indicates the proportion of the cover-crop relative to other species and the proportion of grasses in the Roundup(r)-only and Poast Plus(r) treatments. Graph B shows the cover of all species at 0.6 m above ground, the average height of seedling foliage. Letters above bars indicate statistical significance using Fisher's least significant difference for mean separations (α = 0.05).

tree seedlings, height growth was greater in the cover-crops compared to the herbicide-only treatments. Even in the rye treatment, which had the lowest survival, the remaining live seedlings grew more than the herbicide-only treatments. This result may be attributable to disking that occurred in the rye treatment plots. Disking seemed to provide a good planting medium, which may lead to a more effective capture of adequate moisture and nutrients for seedlings. Disking also slows the initial growth of resident vegetation early in the growing season, during the time many seedlings are developing their first flush.

For most species, seedling survival exceeded 90 percent and only cottonwood, sycamore, and pecan exhibited low survival (Fig. 2). Height growth, however, varied substantially among species. Green ash and white ash provided the best height growth for the light-seeded species, and both had 96-percent survival (Fig. 3). Eastern cottonwood had low survival, but surviving cuttings grew nearly 0.5 m. One reason for the variable results of cottonwood is that they were planted as cuttings, which often have lower survival (Kabrick and others 2007). In addition, it was found later that a number of these cuttings were planted with the lateral buds facing down, which likely caused reductions in survival and growth. For the hard-mast-producing species, swamp white oak had the best survival and growth, with averages that often surpassed that of green ash. Northern red oak and white oak also had higher survival and growth. For each species, height growth was greater than 5.0 cm.

At all sites, the annual nurse-crops (i.e., annual wheat and Korean lespedeza) for the clover and rye treatments were established with success, which helped reduce density of early volunteer vegetation in these treatments. In most cases (except for the rye treatment), the perennial cover-crops were successfully established. The ladino clover germinated uniformly at all sites and was 18 percent of the total vegetation density at time of sampling. During this time, the clover was probably past its peak growth while other vegetation was maturing, which may have resulted in lower numbers than if the data had been collected earlier in the growing season. The redtop established well at two of the three sites, and totaled 31 percent vs. 56 percent resident vegetation (at ground level). In terms of area covered by competing plant material, the Poast Plus® and redtop seem to be the most effective means of vegetation management.

Restoration Implications

Planting hardwood seedlings in drought-prone regions like the Missouri Ozarks can be difficult. Soil conditions even in floodplains can be water-limiting for extensive periods of time. Competition from aggressive, early-successional vegetation, and occasional seasonal flooding can make the task even more cumbersome. It is likely that the species and treatment results we reported will change in coming years. However, initial stages of this type of restoration effort can have important long-term consequences for the growth and development of riparian forests. Species like swamp white oak and green ash each exhibited high survival and growth under these difficult conditions. In addition to being good competitors in a weedy and dry environment, swamp white oak and green ash seedlings are well adapted to the seasonal flooding that will inevitably occur in the future (Burns and Honkala 1999, Kabrick and others 2007). Management treatments such as planting redtop or clover cover-crops and conducting timely follow-up herbicide applications of Poast Plus® may result in a less dense and less-competitive ground flora layer. Annual follow-up management and selecting a variety of bottomland species native to your region are suggested to ensure successful establishment of a riparian afforestation project.

ACKNOWLEDGMENTS

We thank the Missouri Department of Conservation (MDC) site managers -- David Rowold, Marty Calvert, and Brian Hall -- for providing us valuable input and their riparian sites for the present research. We also thank MDC Forest Systems Field Station Supervisor Dr. Tom Nichols for supporting our project and providing funding. Greg Hoss (MDC) provided the seedlings. Dr. Jerry Van Sambeek provided his expertise in seedling physiology and tree plantation management. Dennis Meinert (Missouri Department of Natural Resources) mapped the soils at our sites, and Aaron Stevenson (University of Missouri) provided helpful input on statistical programming during data analysis. Finally, we would like to thank the dozens of field technicians for their hard work and countless hours spent in planting trees and collecting data for this project.

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EFFECTS OF DEER EXCLOSURES ON OAK REGENERATION IN CLOSED-CANOPY STANDS

Angela M. Yuska, Kim C. Steiner, and James. C. Finley[1]

Abstract.—Studies of the effects of high deer densities on forest regeneration have shown altered species composition and reduced diversity in stands regenerating after harvest. The effects of browsing in fully stocked, undisturbed stands are less well known but important, as establishment of seedlings of oaks and other species prior to disturbance is very important for self-replacement. The purpose of this study was to quantify the effects of deer exclusion on existing cohorts of advanced oak seedlings in closed-canopy, mixed-oak stands in Pennsylvania. Permanent plots in six stands were established and measured in 2003, and half of each stand was subsequently fenced. The stands were remeasured in 2006 to quantify changes in the size and number of tree seedlings after two growing seasons as a result of protection from deer. Three additional stands were measured and fenced without controls for periods of 6 to 8 years. In general, fencing enhanced seedling abundance in stands that had good mast crops or reduced seedling mortality in stands that did not. Fencing also was associated with improvements in seedling height. None of the stands fenced for only 2 years exhibited marked improvements in the quality of advance oak regeneration. Two stands that were fenced for 6 to 7 years, both of which had relatively open understories, exhibited significant and rather substantial increases in oak seedling density, frequency of occurrence, and height. A third stand, which was fenced for 8 years and had heavy mountain-laurel cover, exhibited a significant but very small increase in oak seedling height but no lasting increases in seedling density or frequency of occurrence. The results show that preharvest fencing designed to enhance the level of oak advance regeneration may require several years to be effective and may need to be combined with stand thinning or other forms of vegetation control.

INTRODUCTION

High densities of white-tailed deer (*Odocoileus virginianus* Zimm.) can have profound influences on forest stands. Browsing can influence the ability of forests to regenerate after a disturbance such as harvesting because large populations of deer reduce the occurrence and density of seedlings of some species (Anderson and Loucks 1979). In Pennsylvania, high deer populations are known to influence regeneration in forest stands either through general regeneration failure (Marquis and others 1976, Marquis and Brenneman 1981) or reduced diversity of tree species following selective browsing (Bowersox and others 1995). In particular, Pennsylvania mixed-oak stands are inclined toward regenerating non-oak species, a shift that can be at least partially attributed to high deer densities (Gould and others 2005). Black birch (*Betula lenta* L.) and red maple (*Acer rubrum* L.) frequently replace oaks following harvests in central Pennsylvania (Fei and others 2005, Gould and others 2005, Abrams and Nowacki 1992). If high deer densities are present for a long time, vegetation composition can be shifted toward fewer species dominated by those not preferred by deer (Rossell and others 2005). The mixed-oak forests of Pennsylvania contain chestnut oak (*Quercus montana* Willd.), white oak (*Q. alba* L.), northern red oak (*Q. rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Münchh.) as dominant overstory trees in different combinations and densities. Changes in understory vegetation composition, an overall reduction in species diversity, and a transition from forests dominated by oak species to red maple are possible long-term consequences of high deer densities in mixed-oak forests.

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Advance regeneration, regeneration present in advance of harvest or disturbance, is important for replacement of oak in forest stands (Abrams 1992, Larsen and Johnson 1998, Gould and others 2005, Sander 1972). Oak advance regeneration grows more quickly than newly germinated oaks because established seedlings have large, well developed root systems (Larsen and Johnson 1998). Quick growth aids in escaping competition, as advance oak regeneration or sprouts from advance regeneration are often able to compete successfully after heavy cutting (Lorimer 1984, Sander 1972). Deer herbivory and seed predation can reduce the abundance, survival, and height growth of advance oak regeneration, therefore limiting the ability of oak to be replaced successfully when harvest or disturbance occurs.

OBJECTIVES

Although fencing after harvest is commonly employed in areas with high deer densities, post-harvest fencing alone cannot compensate for inadequate advance regeneration, which is considered so important to oak regeneration success. By contrast, very little is known about the responsiveness of regeneration to preharvest fencing, i.e., protection from deer in closed-canopy stands (Rossell and others 2005, Griggs and others 2006). The purpose of this research was to quantify the effect of preharvest fencing on advance regeneration of oak. Aside from its obvious silvicultural implications, studying the effect of fencing in mature stands can provide further insight into the overall impact of high deer populations in mixed-oak forests.

STUDY AREAS

For this study we measured nine mixed-oak stands, 36 to 71 acres in size, located in the Ridge and Valley and Appalachian Plateau provinces of Pennsylvania. All are on state lands managed by the Department of Conservation and Natural Resources (Pennsylvania Bureau of Forestry). The stands occur in an area covering approximately the central one-half of the state from north to south and the central one-fourth from west to east. Elevations range from 950 ft MSL in the Ridge and Valley province to a high of 2000 ft MSL on the Appalachian Plateau. Soils include loams from the Laidig, Dekalb, Ungers, and Wharton series. In all stands, oak makes up the plurality of basal area (39 to 60 percent), which ranges from 106 to 136 ft^2ac^{-1}. All are fully stocked to overstocked (Gingrich 1967). The principal oak species is chestnut oak in 6 stands, northern red oak in 3 stands, and black oak and white oak in one each. Understories are dominated by mountain-laurel (*Kalmia latifolia* L.), huckleberry (*Gaylussacia* spp. Kunth), striped maple (*Acer pensylvanicum* L.), hayscented fern (*Dennstaedtia punctilobula* (Michx.) T. Moore), or combinations of these species. Regionally, mean annual precipitation is 38 to 40 inches and length of the frost-free growing season is 130 to 170 days, but both vary with elevation and topography (Cuff and others 1989).

Six stands (stands 1-6) were measured initially in summer 2003 and half of each stand was subsequently fenced with 8-ft, woven wire fencing to exclude deer. These "divided stands" were measured again in 2006 after approximately two growing seasons and one to three autumns (depending on stand) following fence installation.

In three additional stands, the entire stand was operationally fenced with 8-ft woven wire shortly after measurement and unfenced comparisons were not available. In these stands, fencing treatment effects cannot be isolated because of the lack of controls, but these stands are significant because they were fenced much longer than the six described previously. Bell Furnace I was measured and fenced in the summer of 1997 and remeasured in 1998 and 2004 (after which the stand was harvested). Bell Furnace II was measured in 1998, fenced the following winter, and remeasured in 2004. Finally, Horsepath was measured in 1997, fenced the following winter, and remeasured in 1999, 2005, and 2006. We observed little or no browsing within the fenced portions of any of the nine stands and believe that the fences were generally effective in their intended purpose.

METHODS

Measurements of overstory and understory site and vegetation parameters were taken on permanent plots arranged systematically in a square grid with the area of the stand determining the number of plots, which range from 15 to 40 per site. Each plot consists of a 1/20 acre (26.4-ft radius) overstory plot and four understory milacre (3.72-ft radius) subplots arranged 16.5 ft away from plot center on the cardinal directions. The 1/20 acre plot was measured for overstory and site conditions, and trees with diameter at breast height (d.b.h.) greater than 2 inches were tallied by species. Measurements of vegetation cover and regeneration counts were taken on milacre subplots. Percentage low cover was visually estimated as percentage of projected vegetation cover, by species or species group, in increments of 5 percent for vegetation ≤5 ft in height, and overhead canopy cover was estimated using a convex-spherical densiometer. Tree regeneration data were tallied by counts of tree species in height groups (0 to 2 inches, >2 to 6 inches, >6 inches to 1 ft, >1 to 2 ft, >2 to 3 ft, >3 to 4 ft, >4 to 5 ft, and >5 ft). The dominant oak (largest healthy oak seedling) on each subplot was identified by species, and its height and basal diameter were recorded.

All statistical analyses were conducted using SAS/STAT System Release 9.0 (SAS Institute Inc. 2004). A generalized linear model with a logistic regression form and binomial distribution (SAS PROC GENMOD) was used to examine the effect of fencing or time under fence on changes in oak occurrence frequency for the divided stands. Changes in oak occurrence frequency at Horsepath and Bell Furnace I and II were analyzed using the chi-square test (SAS PROC FREQ). Three additional response variables, changes in mean oak density, height, and height of the dominant seedling on a plot, were evaluated using analysis of variance (SAS PROC GLM) for the divided stands. Residuals of these variables were tested for normality using the Shapiro-Wilk test and for homogeneity of variance using the Levene test. Stand 4 had a large mast crop in fall 2005 and was alone among the divided stands in experiencing a large influx of new oak seedlings during the period of study. Stand 4 was therefore omitted from the combined ANOVAs because including it would have clouded interpretation of the results. The Wilcoxon rank-sum test (SAS PROC NPAR1WAY) was used to analyze the Bell Furnace I and II and Horsepath stands because their data did not meet the normality assumption.

RESULTS

Oak Occurrence Frequency

In the divided stands (excluding stand 4) there was an overall decrease in oak occurrence frequency between 2004 and 2006, and the difference was less for fenced than for unfenced areas (1.5 versus 7.2 percent) (Table 1). However, fencing was not a significant effect ($p = 0.076$) and neither was period of time fenced ($p = 0.873$). Although no notable seed crops were observed except in stand 4, it can be assumed that some acorns were produced each year and, because of this, slight increases in seedling abundance could occur. Only one stand (stand 6) experienced an increase in oak seedling frequency, an accumulation that occurred only in the protected part of the stand (a change from 26.8 to 39.4 percent). All of the unfenced areas of the divided stands experienced a decrease in occurrence frequency of oak seedlings. Stand 4, which had a large seed crop in 2005, showed similar increases in fenced and unfenced areas when measured in 2006.

Table 1.—Characteristics of oak advance regeneration in six mature, mixed-oak stands in which half the stand was protected for deer fencing for 2 years and half left unprotected

Stand	Treatment	# of plots	Frequency (%)		Seedling density (thousands/acre)		Mean dominant height (ft)		Mean height (ft)	
			2003	2006	2003	2006	2003	2006	2003	2006
1	Unfenced	80	88.8	76.3	4.67	2.95	0.61	0.49	0.44	0.42
	Fenced	80	86.3	80.0	6.50	3.88	0.60	0.59	0.45	0.48
2	Unfenced	76	72.4	68.4	4.93	3.87	0.80	0.97	0.59	0.70
	Fenced	79	86.1	86.1	8.33	6.63	0.65	0.93	0.52	0.69
3	Unfenced	72	36.1	29.2	2.65	1.26	0.40	0.43	0.37	0.39
	Fenced	80	26.3	25.0	0.73	0.64	0.34	0.38	0.32	0.35
5	Unfenced	60	90.0	81.7	25.77	13.85	0.60	0.59	0.37	0.38
	Fenced	60	85.0	70.0	8.00	4.40	0.39	0.44	0.32	0.35
6	Unfenced	71	39.4	29.6	0.74	0.71	0.32	0.32	0.32	0.32
	Fenced	71	26.8	39.4	0.84	0.87	0.32	0.34	0.32	0.33
Total	Unfenced	359	63.9	56.7	7.04	4.71	0.60	0.64	0.44	0.47
	Fenced	370	60.2	58.7	4.17	3.22	0.55	0.66	0.42	0.49
4	Unfenced	76	40.8	67.1	1.80	4.53	0.39	0.44	0.37	0.35
	Fenced	80	48.8	76.3	3.56	5.60	0.36	0.43	0.34	0.37

Horsepath initially gained in oak occurrence frequency after the fencing treatment, but then decreased significantly to below pretreatment levels ($p < 0.05$) (Table 2). In contrast, the Bell Furnace stands showed increases in oak occurrence frequency through the entire fencing period, with a significant increase in oak occurrence frequency for both fenced stands by 2004 ($p < 0.05$) (Table 3).

Oak Seedling Density

Although seedling density decreased during the study in both unfenced and fenced portions of the divided stand study areas (except stand 4), the protected areas lost fewer seedlings than unfenced areas (Table 1). By 2006 the unfenced areas had lost an average of 2,330 seedlings per acre compared to 950 for fenced areas ($p = 0.018$). Increases in seedling density as a result of the seed crop in stand 4 were similar between fenced and unfenced areas ($p > 0.05$).

The Horsepath stand experienced a significant ($p < 0.001$) increase of 2,680 seedlings per acre after 1 year of fencing, undoubtedly because of a good seed crop in fall 1998, but seedling density then declined to below the initial level by the time of the 2005 and 2006 measurements (Table 2). Both Bell Furnace stands exhibited rather substantial and significant ($p < 0.02$) increases in oak seedling density after the 1998 measurements, and the increases were sustained until the final measurements in 2004 (Table 3).

Mean Height of Dominant Oak Seedings

The mean height of the dominant oak seedling on milacre plots appeared to be marginally enhanced by fencing for two growing seasons in divided-stand study areas (Table 1), but the effect (if real) was not significant ($p = 0.142$). Results were similar for stand 4.

Table 2.—Characteristics of oak advance regeneration in the Horsepath stand, fenced to exclude deer beginning in winter 1998 (99 sample plots)

	1997[1]	1999[1]	2005[1]	2006[1]
Density (thousand/acre)[2]	1.77[a](0.283)	4.45[b] (0.763)	1.93[a] (0.404)	1.06[a](0.219)
Mean dominant height (ft)[2]	0.41[a](0.030)	0.41[a] (0.020)	0.49[b] (0.034)	0.54[b](0.047)
Mean height (ft)[2]	0.36[a](0.036)	0.36[ab](0.032)	0.47[ab](0.039)	0.54[b](0.047)
Frequency[2]	55.0[ac]	66.7[a]	52.0[bc]	40.4[b]

[1]Standard errors are shown in parentheses.
[2]Means within a row that are not followed by the same letter differ significantly at $p < 0.05$.

Table 3.—Characteristics of oak advance regeneration in the two Bell Furnace stands, fenced to exclude deer beginning in summer 1997 and winter 1999, respectively

	1997[1]	1998[1]	2004[1]
	---------------------Bell Furnace I (116 plots)---------------------		
Density (thousand/acre)[2]	4.89[a](0.715)	5.22[a](0.762)	10.64[b](1.373)
Mean dominant height (ft)[2]	0.68[a](0.048)	0.67[a](0.042)	0.89[b](0.064)
Mean height (ft)[2]	0.42[a](0.020)	0.40[a](0.018)	0.61[b](0.028)
Frequency[2]	71.7[a]	70.8[a]	84.2[b]
	---------------------Bell Furnace II (80 plots)---------------------		
Density (thousand/acre)[2]	-	3.94a(0.763)	7.85[b](1.130)
Mean dominant height (ft)[2]	-	0.62a(0.049)	0.90[a](0.116)
Mean height (ft)[2]	-	0.40a(0.020)	0.85[b](0.044)
Frequency[2]	-	61.4a	77.5[b]

[1]Standard errors are shown in parentheses.
[2]Means within a row that are not followed by the same letter differ significantly at $p < 0.05$.

The mean height of dominant oak seedlings increased from 0.41 to 0.54 ft ($p = 0.01$) during the 9-year duration of observations at Horsepath (Table 2), from 0.68 to 0.89 ft ($p = 0.01$) over 7 years at Bell Furnace I (Table 3), and from 0.62 to 0.90 ft ($p = 0.12$) over 6 years at Bell Furnace II (Table 3).

Mean Oak Seedling Height

The mean height of all measured oak seedlings increased slightly between 2003 and 2006 in most divided stand study areas (Table 1). The increase was larger in fenced plots, but not significantly so ($p = 0.350$).

The mean height of seedlings at Horsepath increased from 0.36 to 0.54 ft between 1997 and 2006 ($p < 0.01$). Similar growth was observed at Bell Furnace I (from 0.42 to 0.61 ft, $p < 0.001$) and Bell Furnace II (from 0.40 to 0.85 ft, $p < 0.001$).

Effect of Covariates

Analyses of the effects of covariates on response variables in divided stands (excluding stand 4) revealed no significant effects of overhead canopy cover on oak seedling abundance or size. However, high levels of low cover (≤5 ft) were associated with greater reductions over the 3-year duration of the study in seedling density ($p = 0.028$) and smaller increases in mean oak seedling height ($p = 0.002$) and dominant seedling height ($p < 0.001$).

DISCUSSION

Estimates of deer densities for the areas encompassing our study stands ranged from 12 to 23 per square mile in 2004 and 2005 (Pennsylvania Game Commission 2006). Current deer densities, although generally lower than in recent decades, are greater than those thought to be present before European settlement (Seton 1909, McCabe and McCabe 1984) and are much greater than densities during the early 1900s when deer were nearly extirpated from Pennsylvania (Redding 1995, deCalesta 1997). Deer density, although a helpful tool to land managers, oversimplifies the complex relationship between habitat and deer. Not only are deer densities greater than those believed to be "natural", but the habitat for advance regeneration of oak (and for deer) has changed with the widespread emergence of a substantial mid-story population of red maple, thought to be attributable to active control of wildfires during the past century (Lorimer 1984, Abrams 1998). Red maple is less preferred as browse than oak, and closed-canopy, mixed-oak forest as represented by most of the stands in this study may provide less browse than what occurred historically, especially following decades of overbrowsing. Furthermore, vegetation growing in low light conditions may be particularly sensitive to the effects of herbivory (Maschinski and Whitham 1989, Baraza and others 2004).

Not surprisingly, protection from deer did not invariably enhance the abundance of oak regeneration in our study stands, since seedling abundance can increase appreciably only in the infrequent event of a good mast crop (Sharp and Sprague 1967, Auchmoody and others 1993, Sork and others 1993). Only one of the six divided stands (stand 4) had a significant mast crop during their 2 years of study, and fenced and unfenced areas in that stand both had similar increases in seedling density and frequency of occurrence on sample plots when measured the following July. The other divided stands, on average, sustained decreases in both density and frequency, but fencing against deer predation significantly reduced the net loss of seedlings per acre.

Both Bell Furnace stands, which were fenced for 6 to 7 years, experienced substantial and sustained increases in oak seedling density and frequency over the course of the study. The lack of controls for those stands makes it impossible to know whether fencing was responsible for their increases in advance regeneration. Nonetheless, that seems likely to be the case because their final densities were quite high for typical (unfenced) stands in this region of Pennsylvania (Steiner and Finley, unpublished data). In contrast, the Horsepath stand, which was fenced for 8 years, experienced large initial increases in both density and frequency of oak seedlings but subsequently declined in both measures of abundance to levels less than those present in 1997. The difference in outcome at Bell Furnace I and II vs. Horsepath is probably attributable to their very different understory conditions. Both of the Bell Furnace stands, although fully stocked in the overstory, contain sparse levels of understory and mid-canopy vegetation, while Horsepath has a dense understory of mountain-laurel and other tall shrubs. The presence of low shade under a full forest canopy can significantly reduce oak seedling growth and survival even in the absence of deer browsing (Miller and others 2004). This conclusion – that low shade at Horsepath prevented advance regeneration from responding to protection from deer – is bolstered by our finding that the level of low shade (≤5 ft) was significantly associated with reduction in oak seedling density and an inhibition of growth.

We observed significant increases in seedling height as a result of fencing in the divided stands or subsequent to fencing in the Bell Furnace I and II and Horsepath stands. However, the increase in mean seedling height was less than about 5 inches even in those stands that were fenced for 6 to 8 years, and it was quite negligible in those that were fenced for only about 2 years. As mentioned, low vegetation cover was significantly and negatively related to height growth, and it is probable that competition for light, water, and nutrients in these fully stocked stands was generally inhibitory to seedling growth even where deer browsing was not a factor.

Both Bell Furnace stands accumulated several thousand additional oak seedlings per acre while protected from deer, and the seedlings grew significantly in height. Based on current guidelines for regenerating oak in this region (Steiner and others 2008), both stands accumulated sufficient advance regeneration of oak to regenerate to a predominance of oak following harvest, and in fact they were harvested in 2005 and 2006.

In contrast, oak advance regeneration did not accumulate at Horsepath in spite of 8 years of protection from deer, although seedlings did become slightly larger. If Horsepath were harvested in its current state it would regenerate primarily to red maple with minor components of chestnut oak, northern red oak, white oak, and eastern white pine (*Pinus strobus* L.). Our experience with this stand makes it clear that protection from browsing, even if continued for many years, does not in itself ensure the establishment of a healthy cohort of advance regeneration.

Protecting advance regeneration from deer for 2 years had a significant effect on oak seedling density, but overall effects on the strength of the cohort of oak advance regeneration were negligible. Protection for longer periods may be effective in building a strong cohort of advance regeneration (Bell Furnace I and II), but even long-term protection will not guarantee this outcome in the presence of high levels of low shade (Horsepath). Although our study did not directly address the influence of shade and other manifestations of competition on oak seedling growth, it is apparent that protection from deer may have to be combined with some form of stand thinning or other competition control in order to be fully effective, especially where substantial levels of low shade are present. The growth and survival of small oak seedlings in the forest understory can be greatly enhanced by partial removal of shade, perhaps combined with fire (Loftis 1983, Loftis 1990, Brose and others 1999, Miller and others 2004). Mid-canopy and understory shade in our stands arises almost entirely from species that are generally avoided by deer, and their predominance is likely a result of decades of high deer populations. Overcoming the ecological legacy of decades of overbrowsing may require more than simply protecting new oak regeneration from deer.

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FOREST PRODUCTS

CONSUMER RING COUNT AND GRAIN TEXTURE PREFERENCES OF SELECTED EASTERN UNITED STATES HARDWOODS

Delton Alderman, Matthew Bumgardner, Scott Bowe, and David Brinberg[1]

Abstract.—Historically, eastern hardwoods have been a staple of forest products production. However, hardwood producers are now faced with serious challenges from substitutable products, such as imports of foreign species, utilization of foreign species in overseas manufacture (e.g., case goods, etc.), and composite-based materials that are imported or manufactured here in the United States. In today's globally competitive marketplace, product distinction is a key to success. Without a functioning manufacturing base, forest management and subsequently forest health, sustainable forestry, and markets for U.S. timberland owners are potentially diminished. Consumer data for ring-density count and grain texture preferences were collected via field studies at several sites in the U.S. The results are directly applicable to forest management of the eastern hardwood resource and afford forest managers the opportunity to manage hardwood forests with the ultimate consumer in mind. Findings from the ring density and texture attributes (i.e., grain) are directly applicable to forest management schemas for the eastern hardwood resource. For example, should a forest manager apply timber stand improvement or single tree selection to attenuate or amplify wood characteristics and/or attributes?

INTRODUCTION

Hardwood lumber in the eastern U.S. is unique because of the large number of marketable species and price variability across species (Luppold and Prestemon 2003). Hardwood has been a staple of forest products production with products ranging from barrel staves to cabinetry to flooring to moulding. Each hardwood species has a unique array of physical attributes, including ring count (e.g., fine, medium, and loose), grain texture (e.g., fast-slow, slow-fast growth patterns [variable vs. consistent]), color, and machinability. Hardwood value is primarily derived from those physical attributes that collectively comprise the appearance attributes color, grain, and texture. However, hardwood producers and manufacturers now confront unprecedented challenges from substitutable products, notably imports of foreign species, both hardwood and softwood; nontimber species (e.g., bamboo); U.S. softwoods; and composite-based materials. For instance, Burgess (1998) reports that the simulation of both wood grain and color in plastic products is being utilized successfully in the production of siding, and outdoor furniture, and for other applications. Burgess(1998) also notes that products are being developed for new markets.

In today's globally competitive marketplace, product distinction is a key to success. However, prices can change due to exogenous factors such as fashion, demand, and substitutability. For example, Luppold and others (2001) reported that in January 1968 grade No. 1 Common 4/4 Appalachian yellow-poplar's price was 33 percent greater than that of No. 1 Common 4/4 red oak; but by January 1993 No. 1 Common red oak was 136 percent greater than yellow-poplar. The reversal in relative prices of these two species is primarily attributed to pricing and supply pressures resulting from fashion and style changes.

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Historically, U.S. furniture was manufactured primarily with U.S. hardwoods. Approximately 1.5 billion board feet of lumber was used in furniture manufacture in 2003, about 15 percent of the hardwood lumber production for that year (Luppold 2004). China imported more than 25 million m^3 of logs in 2002, a 50 percent increase in volume and a 20 percent increase in value as compared to 2001. Sawn wood imports (5.5 million m^3 - 75 percent of which is hardwood) increased 35 percent in volume and 23 percent in value during the same period (International Wood Markets Research 2004). China's primary timber trading partner is Russia, and major border towns in China have increased their populations by an average of 300 percent in reaction to the opportunities in timber trade. Trade in hardwood logs and sawn lumber between the two countries also has escalated greatly since 1997 as a result of the devaluation of the ruble and China's new government-imposed restrictions on the annual timber harvest. Imports have grown from roughly 1 million m^3 per year in 1997 to 10 million m^3 in 2002 and now represent approximately 65 percent of China's log and lumber imports. Log and lumber imports from the Russian Far East are expected to grow further, by at least 10 to 15 percent per year (Wood Markets Monthly 2003).

With unprecedented competitive threats, improving the market environment for eastern U.S. hardwoods is of paramount importance. The viability of diverse manufacturing sectors is at stake, as are healthy forests. If we lack a functioning manufacturing base, forest management efforts will decrease. Forest health will suffer as sustainable forestry initiatives decline. Subsequently, markets for U.S. timberland owners may shrink. Moreover, we also must consider both direct and indirect effects occurring throughout the value chain of wood products manufacturing: timberland owners, loggers, primary manufacturing (e.g., sawmills), secondary manufacturing (e.g., wood components), and service industries (e.g., banking, machinery, mechanical, suppliers).

CONSUMER PREFERENCE

Consumer preference for discrete hardwoods is based on the assumption of a real or imagined "choice" between U.S. hardwoods and alternatives. Consumers may rank alternatives on the basis of one or more dimensions: satisfaction, gratification, enjoyment, or utility the choice provides. How will consumers judge (i.e., evaluate) and express preferences for products manufactured from discrete hardwood species and man-made materials?

Findings from the ring density and texture attributes (i.e., grain) are directly applicable to forest management schemas for the eastern hardwood resource. For example, should a forest manager apply timber stand improvement or single tree selection to attenuate or amplify wood characteristics/attributes?

OBJECTIVES

We had three objectives in our study of consumer preferences for hardwoods and hardwood attributes:

1. To discern if U.S. consumers have a preference for selected eastern hardwood species vs. comparable foreign species and identify attributes, opportunities, and weaknesses of eastern U.S. hardwoods
2. To investigate preferences for ring count and grain texture
3. To determine how differences in select eastern hardwood attributes, if present, might affect the potential use of hardwood in various hardwood sectors.

Table 1.—Natural species contrasts

Species	Norway maple	Rubberwood	Russian birch	Lyptus
Black cherry				x
Sugar maple	x	x		
White oak		x	x	

Table 2.—Species, grain, and grain patterns

Species	Fine Grain,[1,a]	Medium[1,a]	Loose[1,a]	Textured[2]	Finger jointed
Black cherry	x	x	x	x	x
Sugar maple	x	x	x	x	x
White oak	x	x	x	x	x
Rubberwood	x	x	x	x	x
Norway maple	x	x	x	x	x
Russian birch	x	x	x	x	x
Lyptus®	x	x	x	x	x
Cherry laminate[3]		x[3]			
White oak laminate[3]		x			
Hard maple laminate[3]		x			

[1] grain is consistent[a] (e.g., uniform or nearly uniform growth increments).
[2] varied texture.
[3] only 3-laminate tables will be produced, each in the manufacturers' finish.
[a] Fine (≥ 9 rings per inch); Medium (5 to 8 rings per inch); Loose (≤ 4 rings per inch).

MATERIALS AND METHODS

Materials

Thirty-eight hardwood end-tables (approximately 15 in. x 20 in. x 28 in. tall) were manufactured. American species utilized were: black cherry (*P. serotina*), sugar maple (*A. saccharum*), white oak (*Q. alba*); foreign species were Norway maple (*A. platanoides*), rubberwood (*H. brasiliensis*), Russian birch (*B. pendula*), and Lyptus®, sold as a Brazilian cherry (*E. grandis* var. urophylla). End-tables also were manufactured using commercially available man-made laminates that substitute for cherry, oak, and maple. As definitive data regarding actual hardwood consumption are lacking, these species were selected because they represent a spectrum ranging from ring diffuse to ring porous, and for the most part, represent lighter-colored woods.

Further, for each species group, end-tables were produced with the following ring attributes (i.e., rings per inch)—fine (≥ nine rings/in.), medium (five to eight rings/in.), and loose (≤ four rings/in.)—and with varied texture attributes, either fast-to-slow or slow-to-fast (variable growth pattern vs. consistent growth pattern). The natural species material contrast is presented in Table 1 and species and grain patterns are presented in Table 2.

Methods

Utilization attribute information was collected by field studies with the focus on acquiring an in-depth understanding of raw material preferences and material attributes. The studies were executed at

Christiansburg and Tysons Corner, two cities in Virginia, and Madison and Florence in Wisconsin. Individuals were solicited to evaluate the 38 end-tables during a 1-month period, mainly on the weekends. Each subject was paid $10 as an incentive. One-third of the end-tables per week were evaluated to reduce the risk of subject information overload. Subjects evaluated the tables on the basis of species, grain, grain patterns, and color. Later manipulations addressed such variables as country-of-origin and willingness to pay (i.e., price points).

We explored within-group variations by contrasting the tables, demographic variables, country-of-origin manipulations, table/country assessment, and price points to determine the nature of the relationships among variables. Between-group comparisons were accomplished by using several demographic variables (e.g., gender, income, education, and location). Within and between-group contrasts using ANOVA and MANOVA provided relevant information regarding preferences. Analysis also included multidimensional scaling to detect meaningful underlying dimensions that could explain observed similarities or dissimilarities. We also used factor analysis to assess table similarities.

RESULTS AND DISCUSSION

Data collection and analysis are still being completed. Our findings can be linked directly back to the forest as preference data for ring density and texture (i.e., grain) can be applied in the forest by forest managers.

Knowing preferred attributes affords timber manager the opportunity to manage hardwood forests with the final consumer in mind. Additionally, significant competitive advantages could arise as a result of discerning attributes that differentiate eastern hardwoods. For instance, furniture, cabinet, moulding and millwork, and other value-added manufacturing industries of the eastern region would have the opportunity to take advantage of the attribute findings. Increased utilization of locally grown eastern hardwoods may result in improved employment and profitability for the eastern region's mills. Ultimately, stable or increased demand may enhance forest management practices.

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EFFECT OF CURVE SAWING ON LUMBER RECOVERY AND WARP OF SHORT CHERRY LOGS CONTAINING SWEEP

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Abstract.—It has been estimated that approximately one-third of hardwood sawlogs have a significant amount of sweep and that 7 to nearly 40 percent of the yield is lost from logs that have greater than 1 inch of sweep. While decreased yield is important, for hardwood logs the loss of lumber value is likely more significant. A method that produced lumber while accounting for log curvature (sweep) would allow greater volumes and higher value material that would also contain less warp when dried. While this technology is being utilized for softwood processing, it has not been accepted by the hardwood industry.

A lumber recovery study conducted on mostly 8-foot-long grade 2 and 3 cherry logs at a mill utilizing a curve sawing gang, produced greater lumber volumes from cants that were curve sawn than from cants that were straight sawn. Increases in overrun ranged from 6 to 18 percent while lumber recovery improvements ranged from 0.5 to 1.3 for 8-foot logs containing 1-3 inches of sweep. Since the curve sawing gang used in the recovery study was limited in the maximum amount of sweep that could be handled during sawing (1¾-inches per 10 feet), simulation software was used to predict the potential increase in volume recovery of the logs sawn if the machine had been able to handle the maximum amount of sweep. Results indicated that lumber recovery increases proportionally with the amount of sweep in the log assuming that the machine could accommodate maximum sweep. Measurements of warp after drying indicated that the boards produced by curve sawing contained significantly more bow and crook than boards produced by straight sawing. While these differences are significant, the actual amount of bow (less than ½ of an inch) and crook (1/8th of an inch) would not likely significantly impact rough mill yield when processed. Twist was not significantly different between the two groups and did not exceed ¼ inch.

INTRODUCTION

Approximately one-third of hardwood saw logs have a significant amount of sweep, enough to incur sweep deductions of 5 percent or more (Hamner and others 2007). Common hardwood log grading scale deduction estimators predict that approximately 13 percent (range: 7 to almost 40 percent) of the yield from logs that have over 1 inch of sweep is lost (Hamner and others 2007). These yield losses are likely more significant for smaller-diameter logs. Although decreased yield is of importance, the loss of lumber value is probably more significant for hardwood logs. When curved logs are sawn using straight sawing methods, the highest valued material is removed from the outer portions of the log in order to straighten the log for further processing. In so doing, more of the highest quality wood is removed as slab wood destined for the chipper. The remaining lumber will likely be lower in value as it contains portions of the lower grade interior of the log as well as sections from the higher grade exterior.

In addition to volume and value losses, the lumber produced from logs sawn using traditional methods often contains greater amounts of warp when dried due to the severe grain angles produced. A method that produces lumber while accounting for log curvature and sweep would allow for increased volumes and

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higher-valued material that would also contain less warp when dried. This technology is being utilized for softwoods, but the hardwood industry has yet to accept it. Research demonstrating the potential gains by utilizing curve sawing technology would allow for greater utilization of the hardwood resource, increase the value of the material produced, and afford hardwood lumber producers the opportunity to be more competitive.

Curve sawing technology utilizes gang-saw machinery to allow logs or two-sided cants with sweep to be cut parallel to the log surface or axis. There are two basic curve sawing techniques; one method manipulates a curved cant through stationary saws and the other method uses articulating saws that follow the contour of the log. It has been demonstrated that curve sawing technology increased lumber recovery in softwood logs containing sweep (Wang and others 1992). Since curve sawn boards are cut along the grain, the potential for producing higher quality lumber increases. Curve sawn lumber from softwood logs containing sweep are on average wider and longer than lumber sawn using straight sawing techniques (Petree 1998). Softwood lumber recovery in logs using curve sawing techniques was reported to yield increases up to 16 percent (Wang and others 1992). No published information exists about the potential yield increase in hardwood logs, or more importantly about the potential for a grade yield increase.

With the current increase in raw material costs and reduction of lumber prices, the profit margins of hardwood sawmills are decreasing. Any processing method that would allow for an increase in lumber volume concurrent with a value increase would provide an invaluable benefit to the hardwood lumber industry. Therefore, a study was conducted to determine the value and volume improvements that are possible in sawing hardwood logs using curve sawing techniques in comparison to traditional straight sawing methods.

OBJECTIVES

We undertook this study with the following objectives:

1) Compare the lumber grade and yield differences between curve sawing and traditional straight sawing for hardwood sawlogs containing sweep.

2) Compare the amounts of warp that occur after drying for lumber sawn from logs with sweep using curve sawing versus straight sawing techniques.

METHODS

One hundred sixty-two U.S. Forest Service grade 2 and 3 (U.S. Forest Service 1966) cherry logs with small-end diameters of 12-14 inches and lengths of 8-10 feet were selected and measured at a sawmill in Pennsylvania. The logs were measured for length, large-end diameter, and small-end diameter (to enable volume estimation, as well as for log scale deductions (including sweep). Length and diameter limitations were used to keep sample sizes to a minimum, yet provide reliable and repeatable results. The length restriction was a function of logs brought into the mill log yard, as very few logs over 10 feet contained measurable sweep. Logs were separated into two categories, those with 1-3 inches of sweep and those with 3 or more inches of sweep.

Lumber Recovery

Each group of logs was processed separately through the mill. Processing consisted of scanning each log for scaling information, debarking, and processing into a two-sided cant at the band saw headrig, which also had a circle saw chipping head. The logs were processed such that the cants were sawn with the faces being perpendicular to the sweep. Cants were then processed by a curve sawing gang that had an arbor, which could move +/- 4 degrees, and could handle a maximum sweep of 1¾ inches in 10 feet. All lumber produced was 4/4-inch thick. As part of the processing at the gang saw, each cant was scanned using a high-resolution industrial laser profile scanner which measured both the profile and thickness of each cant. After sawing, the outermost board on one side of the cant was marked for warp measurement. All lumber produced by each experiment was graded by a National Hardwood Lumber Association-certified grader and separated by each log grouping for further evaluation. Due to an error in lumber data collection, only the lumber produced from logs within the 1- to 3-inch sweep category was available for accurate recovery comparison.

Warp Evaluation

For each cant sawn, one outside board was marked and measured for bow, crook, twist, and cup. A table developed for the study was used to measure board deviance from flat to 1/8th -inch increments. The lumber was then stacked and dried using a conventional kiln schedule for 4/4-inch cherry. After drying, each marked board was measured for width and length. Each marked board was remeasured for warp, and also every fifth board for a total of 279 boards. Comparisons for cup, bow, twist, and crook were made for each log grade and sawing technique using a two-tailed t-test comparison of means, assuming equal variances and α=0.05.

Simulation Analysis of Curve Sawing

Since the curve sawing gang could process a log only with a maximum sweep of 1¾ inches in 10 feet, simulations were run to determine the potential volume production if greater curvature could have been sawn. Of the 162 cants measured and processed in the sawmill, 104 (64 percent) were 8 foot long, with single sweep ranging from 0.2 to 6.4 inches. Sawing simulations were performed on a sample of these 8-foot cants to compare yield differences between curve and straight sawing. The simulation software used in the analysis was Edger11 (1.0)© developed by Nelson Brothers Engineering (Vancouver, WA).

Before the simulation was performed, the cants were segmented into 1-inch sweep categories. Sweep was determined for each cant by measuring the maximum deviation from a straight line extending from one end to the opposite end. All sweep measurements were performed on the cant images generated by the simulation software. Samples were then pulled from each sweep category to use in the sawing simulation. The following samples were then pulled from each sweep category: Five cants, 0-2.0 inch range; 10 cants each, 2.1-3.0, 3.1-4.0, and 4.1-5.0 inch ranges; and five cants from the 5.1-6.0 inch range (40 total cants). The full dataset of logs sawn was not available due to a data storage error during the recovery study. The distribution of each sample was representative of the larger dataset distribution from which it was obtained.

Sawing simulations were then performed on each of these sample cants using simulation software. First, each cant was straight sawn into 4/4 lumber. No blade movement was allowed during sawing, but skewing of the blades was permitted during sawing. The number of boards produced and the dimensions of each board were recorded. Next, the same cants were curve sawn into 4/4 lumber, allowing the saw blades to pivot during sawing. For the curve sawn cants, a maximum allowable curvature of 6 inches per 8 feet was used. As with the straight sawn lumber, the number of boards and the dimensions of each board were recorded. Based on the dimensions of each board, total volume yield (in board feet) was calculated for each cant while using both the straight- and curve-sawing setups.

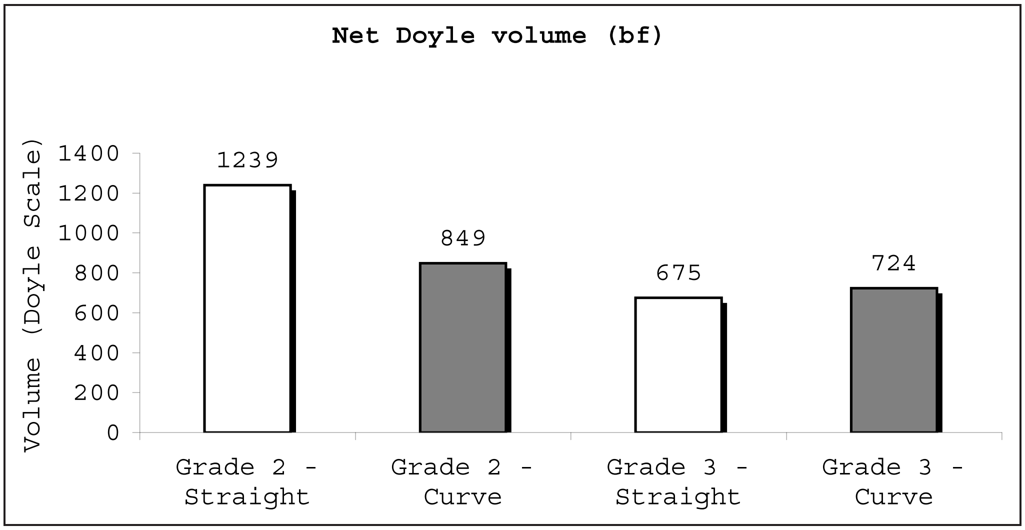

Figure 1.—Net log volume for each group tested (Doyle Scale).

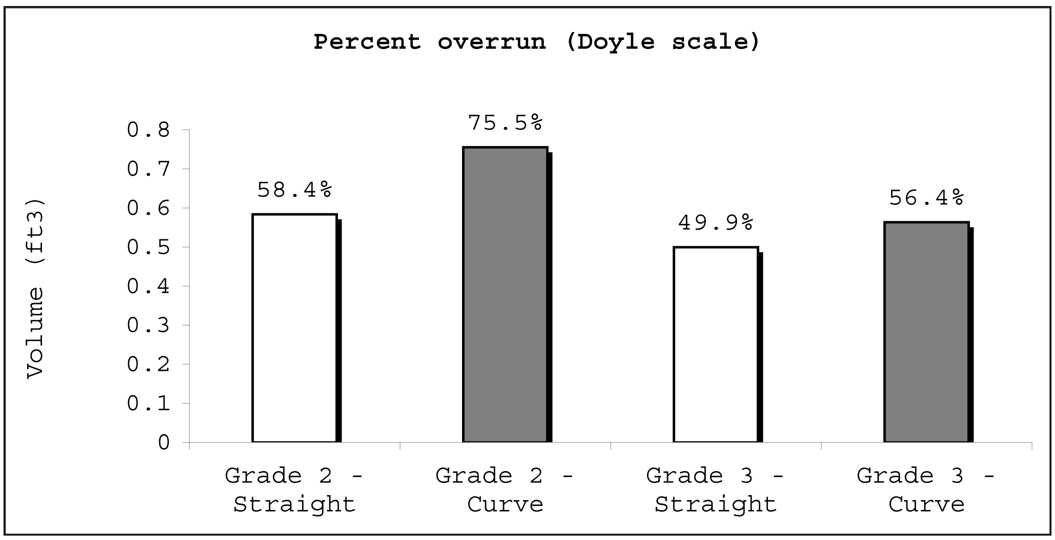

Figure 2.—Percent overrun (Doyle Scale) of each group tested.

RESULTS AND DISCUSSION

One hundred sixty-two logs were measured and processed through the mill. Scan data were collected for all logs; however, a file-saving error resulted in only 104 two-sided cants for use as input in the sawing simulations. Seventy-eight logs were tracked for evaluation of output: for lumber volume and value, and warp after drying. Even though the diameter, length, and sweep distribution (2.5 inches on average) was not significantly different between the log grade sample groups, the net log scale differed for each (Fig. 1); therefore, all data were compared with reference to the input volume.

Volume Recovery

Both lumber recovery factor (LRF) and overrun (based on net Doyle scale) values were calculated for each sample group. Each measure is considered comparable since it is based on the log volume input and the lumber volume output for each log grade and sawing method. Overrun was 18 percent greater for cants produced from curve sawn grade 2 logs and 6 percent greater for cants that were curve sawn from grade 3 logs (Fig. 2). The LRF was 1.3 and 0.5, respectively, greater for cants curve sawn from grade 2 and 3 logs than for

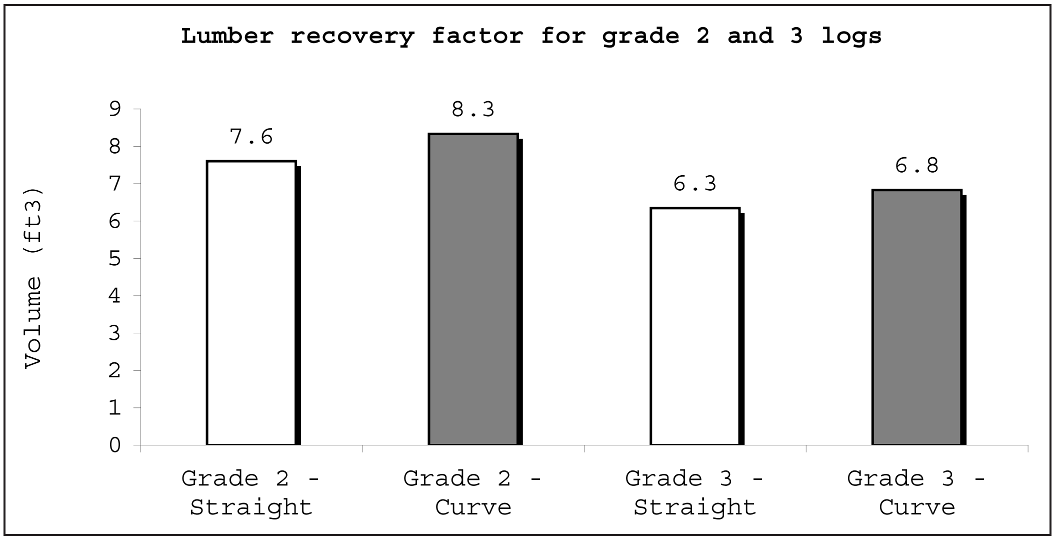

Figure 3.—Lumber recovery factors for each group sawn.

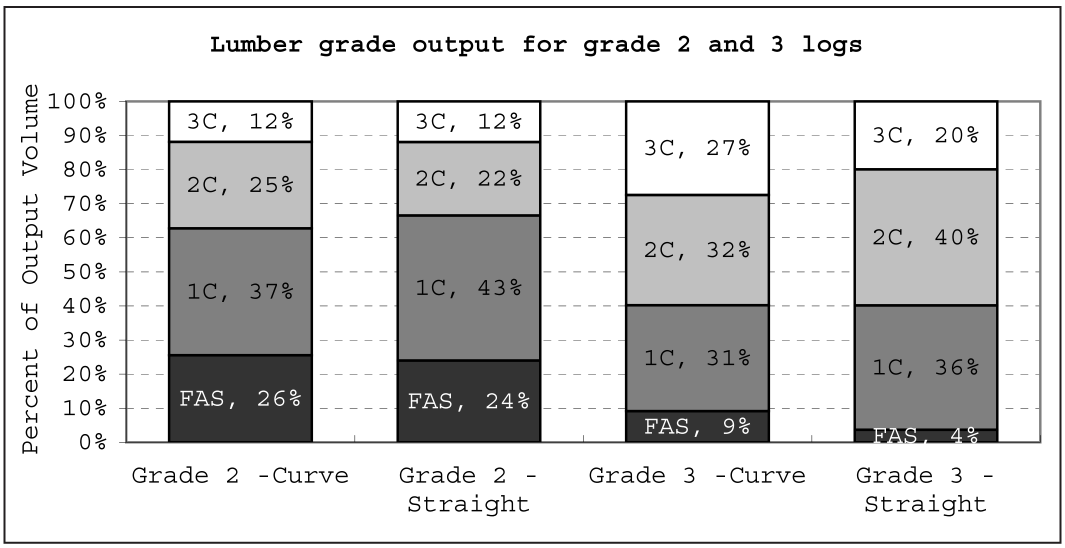

Figure 4.—Percent of lumber grade recovered from grade 2 and 3 logs.

those straight sawn, regardless of log grade (Fig. 3). While Wang and others (1992) reported greater softwood recovery values, their study utilized smaller diameter (4.4 to 7.1-inches) and longer (all 16-foot) logs. The impact of curve sawing on yield is much greater for smaller diameter and longer logs based on a log's geometry. Our values are closer to those reported by the softwood industry (Westergard 1995).

Value Recovery

Figure 4 indicates that curve sawn cants produced greater volumes of FAS lumber than straight sawn cants, regardless of the original log grade. When the lumber value per board of log input is compared (Fig. 5), curve sawn cants produced higher values than those that were straight sawn. Lumber values were determined using values obtained from the Hardwood Review Weekly (2007). The increased value indicates that the ability to curve saw logs (with sweep up to 3 inches) significantly increases lumber value output for grade 2 and 3 cherry sawlogs.

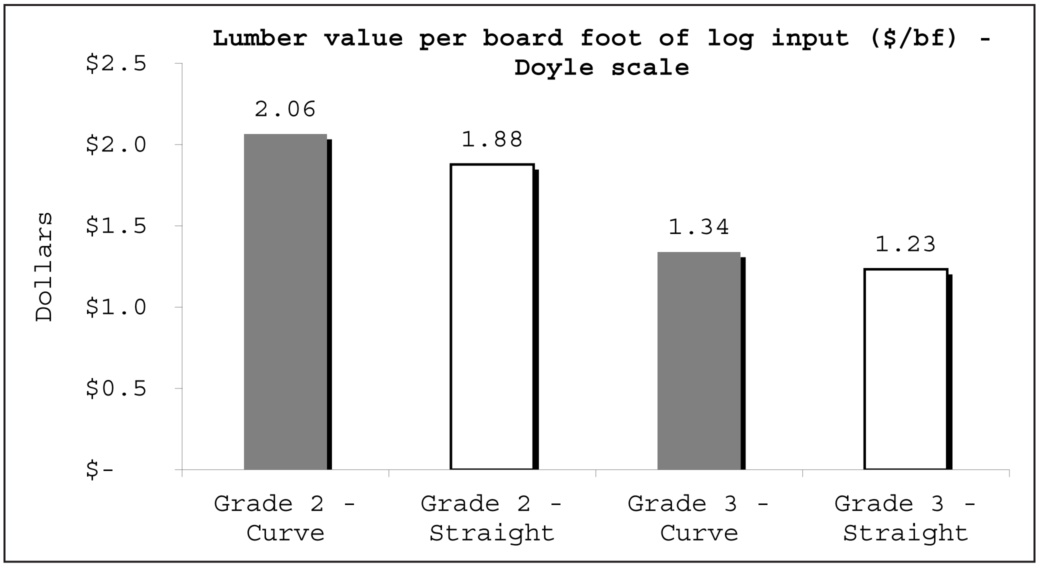

Figure 5.—Lumber value per board foot of log input ($/bf Doyle scale).

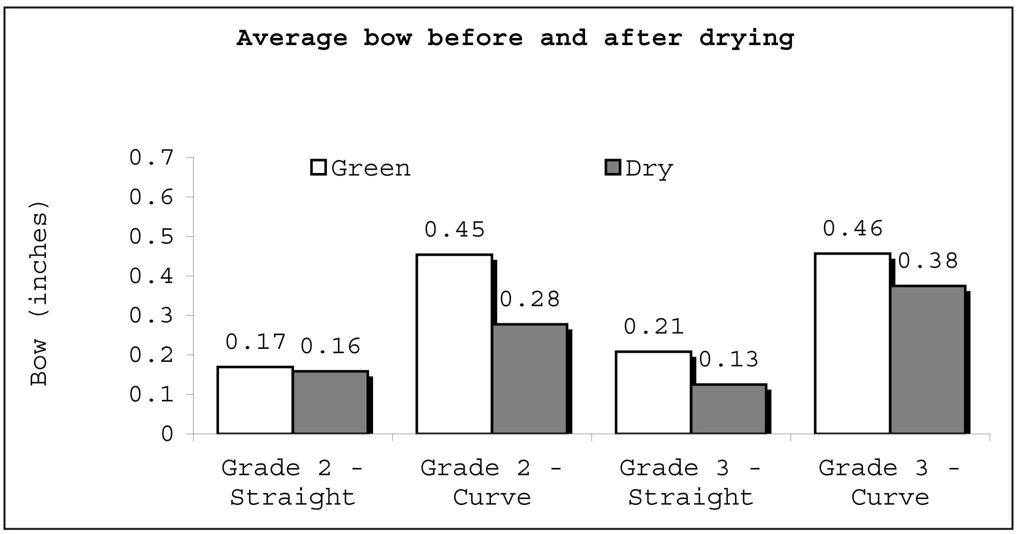

Figure 6.-Average bow in jacket boards measured before and after drying.

Warp

One concern with curve sawing is that the boards produced will have significant amounts of bow. Results of warp measurements for only the jacket boards (those measured both before and after drying) indicated that bow is reduced during the drying process (Fig. 6); however, bow does still exist. When compared with softwood drying results (Bedard and Tremblay 2004), curve sawing hardwood does tend to result in slightly more bow than found in straight sawing logs containing sweep; however, the amount of sweep is no greater than ½ inch in 8-foot lumber (Fig. 7). Crook also was significantly greater for lumber produced by curve sawing; however, the actual difference is approximately $^{1}/_{8}$th of an inch (Fig. 7). Twist was not significant between the two groups for either sawing method or for log grade (Fig. 7). This finding is in direct contrast to the results obtained for softwood (Bedard and Tremblay 2004), where twist was the cause of the greatest amount of degrade.

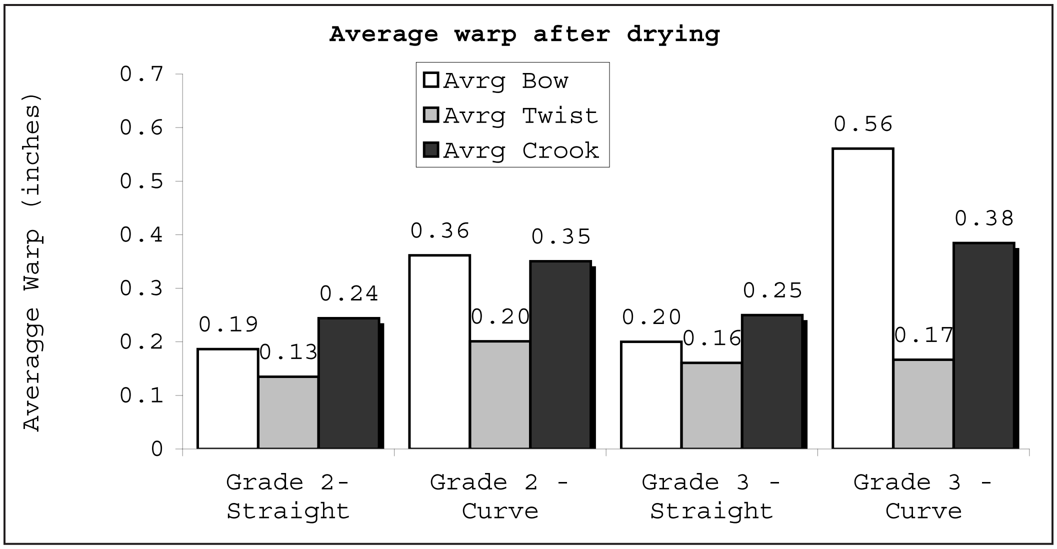

Figure 7.—Average warp (bow, crook and twist) in lumber after drying for each grade and sawing method.

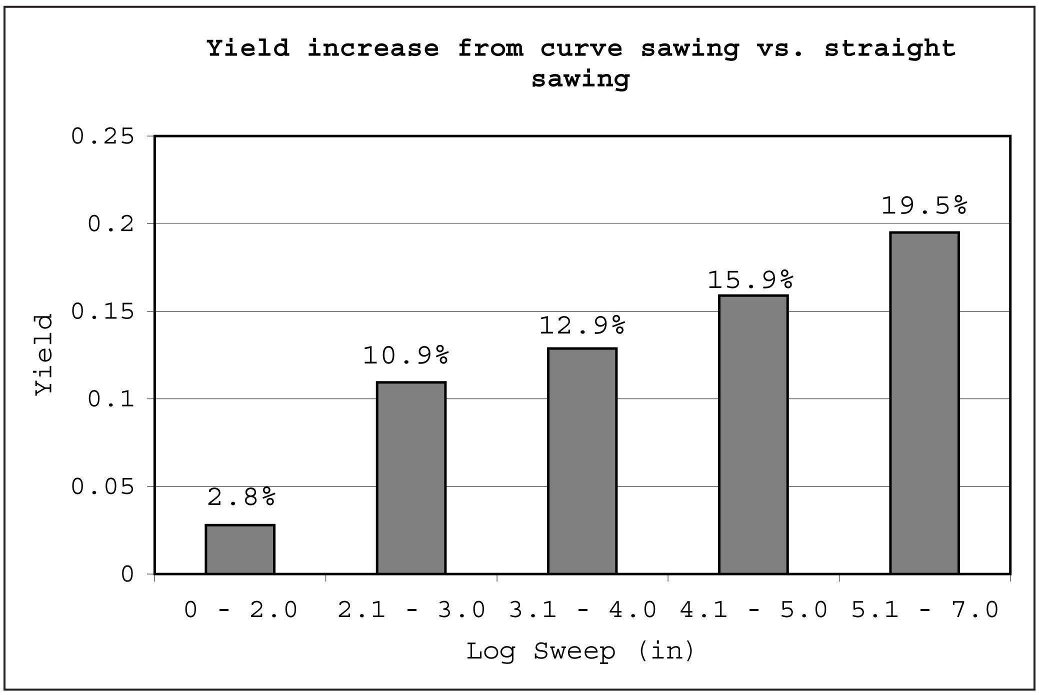

Figure 8.-Yield increase from curve sawing versus straight sawing for simulations.

Simulation

Since the curve sawing equipment used in this experiment was limited due to the amount of sweep that could be tested, cants were measured and tested using simulation to determine if greater recovery gains could be made with an increase in curve sawing capability. The results indicated that curve sawing definitely results in increased lumber yield, regardless of the amount of sweep that the machine could accommodate (Fig. 8). However, the greatest potential for yield recovery is being able to utilize sawing technology that will handle the maximum amount of sweep within the log. The simulation showed that as the percentage of sweep increased, the ability to recover volume increases proportionally, if the sawing machine can actually process the maximum sweep in the log.

CONCLUSIONS

This lumber recovery study produced greater lumber volumes for curve sawn cants than for straight sawn cants. Increases in overrun for 8-foot logs ranged from 6 to 18 percent and the lumber recovery increase ranged from 0.5 to 1.3 (for 8 foot logs containing 1 to 3 inches of sweep). Boards that were curve sawn did have significantly more bow and crook than boards that were produced by straight sawing. While these differences are significant, the actual amount of bow (less than ½ of an inch) and crook (1/8th of an inch) would not likely significantly impact rough mill yield when processed. Twist was not significantly different between the two groups and did not exceed ¼-inch.

The results clearly indicate that volume recovery is greater when curve sawing hardwood cants produced from logs containing sweep, even when those logs are relatively short (predominantly 8 feet in length). Greater increases would be possible with longer and/or smaller diameter logs. While the curve sawing gang used in the recovery study was limited, simulation software was used to predict the potential log recovery increase if the machine had been able to accommodate the maximum quantity of sweep. Results indicated that lumber recovery increased with the amount of sweep in the log, assuming that the machine could accommodate the maximum sweep in processing. Given that sawmills often spend hundreds of thousands of dollars on new equipment to obtain a 2 percent increase in yield, it is surprising that more hardwood sawmills have not adopted this technology based on the results obtained—as the minimum gain was 2 percent. Not only does this technology result in greater lumber recovery for the species and grade of logs sawn, it resulted in significantly increased value output.

ACKNOWLEDGMENTS

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PRELIMINARY SILVICULTURAL RECOMMENDATIONS AND AN UPDATED ANNOTATED BIBLIOGRAPHY FOR BIRDSEYE SUGAR MAPLE

Don C. Bragg[1]

Abstract.—The birdseye grain abnormality in sugar maple can greatly enhance its commercial appeal. However, birdseye has been opportunistically exploited, without exploring management strategies that can improve its potential. Even though the initiation and development processes of birdseye maple are still largely unknown, useful silvicultural advice can still be provided for timber managers. First, the identification of birdseye maples before felling, or early in the merchandising process, allows for better protection of log value. Second, protecting the residual stand while logging should likewise bolster future stand value by reducing undesired injury and mortality of the residual. Third, because birdseye abundance could be associated with stand density, it may prove advantageous to keep known birdseye trees in denser areas to ensure continued figured wood production. Finally, an additional set of 80 annotated references on birdseye is provided to further research on the topic.

INTRODUCTION

Improving the profitability of forests has long been a goal of timber managers. To date, most of this effort has concentrated on silvicultural practices for increasing growth (for example, site preparation, competition control, thinning, fertilizing). Far less emphasis has been placed on optimizing the value of certain attributes of the trees. While not always present, some of these qualities can greatly enhance the commercial potential of a stand. For instance, the birdseye grain abnormality in sugar maple (*Acer saccharum*) has long been highly prized (Bragg 2006).

However, birdseye maple has long been treated as purely an "accidental" resource, to be exploited as encountered. Such a strategy leaves little in the way of options to fully capture the potential of the birdseye resource. In this paper I will discuss a number of steps that can be taken to improve management practices regarding birdseye maple.

BIRDSEYE-RELATED MANAGEMENT ADVICE

To date, researchers have not identified the formative process(es) leading to birdseye. However, we do know that a number of suggested causes (for example, birdpeck or adventitious buds) do not produce birdseye sugar maple (Bragg 1999, Rioux and others 2003). Birdseye in sugar maple apparently arises from injuries due to pressure exerted upon cambial initial cells, causing abnormalities in their structure and function that are also reflected in associated tissues (Rioux and others 2003). While not giving a specific mechanism, Rioux and others (2003, p. 956) suggest that a physiological disorder resulting from "adverse environmental factor(s)" (perhaps stressful growing conditions, injuries, or pathogens) may lead to birdseye production. It is also possible that multiple triggers could induce birdseye formation (Bragg 1999, Rioux and others 2003), especially in light of the broad but inconsistent geographic distribution of this grain pattern (Beals and Davis 1977, Bragg 1995). Other species may develop birdseye-like grain patterns (for a partial list, see Appendix A and Bragg and Stokke [1999]), but there is no research on anatomical similarities between these grain abnormalities and birdseye in sugar maple.

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Even though we do not yet know enough about birdseye to culture this grain abnormality, there is no reason to “mine” this resource from the landscapes in which it is found. The following suggestions are geared toward increased awareness and preventative measures to protect existing birdseye resources. Unfortunately, truly prescriptive measures intended to sustain birdseye abundance are still unavailable.

Identification of Birdseye Maple

Identification of birdseye maples before felling, or early in the merchandising process, allows them to receive special treatment and thereby helps to preserve their value. Many grain abnormalities, including birdseye, can be recognized prior to harvest if certain characteristics are visible (Pillow 1955, Bragg and Stokke 1994, Velling and others 2000). For birdseye, a basal bole constriction is sometimes apparent, or the “eyes” can be spotted on the surface of the bark (Mroz and others 1990, Bragg and Stokke 1994). If these more obvious characteristics are not visible, then the bark and wood of standing trees can be further explored in a nondestructive but potentially injurious examination (Bragg and Stokke 1994). In areas with relatively abundant birdseye, timber cruisers should be trained to identify figured maples so as to improve the bidding process (Bragg 2006).

It is critical that foresters help their clients realize the value of all of the timber attributes, especially private timberland owners with little knowledge of forest products. Even if they do not have birdseye maple, other types of figured wood can be found in virtually every forest, and these may also yield valuable products (Bragg 2006). Burls or curly grain, for example, are sometimes considered an eyesore or worthless defects. However, most woodworkers prize these abnormalities, and often pay a premium for quality materials (Mitchell 1964, Velling and others 2000). Some are also willing to pay top-dollar for small (otherwise submerchantable) pieces of well-figured wood (Bragg 2006). Marketing this product may require some creativity, but can certainly reward the effort. Simply discarding, relegating to lower-value uses (for example, pulpwood rather than sawtimber or veneer), or even giving away potentially valuable wood are poor ways to maximize the value of the timber for the landowner (Hoffman 2004).

While it is best to identify birdseye maples before they are felled, it is not always possible. Their value can still be optimized, however, if they are recognized before they are fully processed. The cut faces of the logs, when exposed, can be searched for the tell-tale “vestigium” or traces that extend towards the pith, or the surface of the wood can be examined where bark is removed for the “gelasini” or indentations (Bragg 1999). If birdseye maple logs are found, it is often best to set them aside for later evaluation by a birdseye buyer, rather than attempting to buck them at the landing, since these buyers may prefer to process logs themselves. However, these logs should be discreetly placed to minimize theft, a major problem in some areas (Walters 1995, Fullerton 1996, MacLean 1997).

If the birdseye logs are to be bucked, it is imperative to use the most skilled individual possible to process the wood using the least damaging technology. One of the most important things that can be done with hardwood sawtimber is to properly merchandise it; repeated studies have shown that poorly trained workers can drastically reduce value by inappropriate decisions on how to cut the logs (for example, Pickens and others 1992, Boston and Murphy 2003). It is also best to use the saw technology that minimizes kerf and fiber damage so that the birdseye logs can be converted into their highest and best use (Bragg 2006).

Protection of Residual Timber

Protection of the residual stand during and immediately after timber harvesting can help protect future asset value by reducing undesired mortality and decay in the leave trees. In general, the same advice provided for good forestry practices in uneven-aged hardwoods (for example, Godman and Erdmann 1981, Leak and Gottsacker 1985, Erickson and others 1992) holds true for stands with birdseye. For instance, if birdseye maples are to be retained for future harvest, their bole quality should be protected. Decay or stain in such trees can relegate them to low value uses rather than the prized veneer sought by buyers. The steps taken to protect individual birdseye maples, however, may prove more exacting than those used for other hardwoods. Such measures may entail reserving buffer trees around the birdseyes to ensure that felling or skidding operations do not damage the aboveground parts of the tree, or that vehicle traffic does not injure roots.

Under certain conditions, it may actually make more sense to preserve large groups of trees untouched near known birdseyes, rather than partially harvesting them to remove nonbirdseye individuals. Protection from damage is an opportunity cost that must be recognized. The great value disparity between quality birdseye maple logs and even prime but nonfigured veneer logs can justify foregoing cutting now to ensure value in the future. There may also be maintenance issues regarding stand density and birdseye production that would warrant a hands-off approach to groups of trees surrounding birdseye maples.

Density Management and Birdseye Maple

Because birdseye frequency in sugar maple is associated with stand density (Mroz and others 1990, Bragg and others 1997), keeping known birdseye maple residual trees in localized pockets of dense timber could help ensure continued production of the rare figure. Furthermore, there is at least anecdotal evidence of an abrupt cessation of birdseye grain production after competitors had been harvested (for example, Pillow 1930, Constantine 1959). Hence, heavily thinning the overstory adjacent to reserved birdseye maples may provide enough release from adverse conditions to induce the production of "normal" wood, and thus reduce or even eliminate the desired grain condition.

Even if birdseye production does not cease or decline in quality, there may be enough release from a thinning of the overstory to result in a marked increase in diameter growth. Such a change in ring width is not always desirable for veneer-grade trees, since inconsistent ring thickness degrades veneer quality (Alderman and others 2004, Cassens 2004). Birdseye value is directly related to general log quality; cull logs are of little to no value, and there are instances when birdseye becomes just another defect in low-grade sawlogs. In conventional sawlog markets, it is only in the best of logs that a true premium for birdseye is achieved.

Birdseye Maple Sustainability

To date, our inability to successfully culture birdseye maple means that every figured tree harvested may not be replaced on the landscape, suggesting that the long-term sustainability of this resource is dubious. Birdseye abundance appears to have declined from historical levels. Some reports have noted that figured maple (including birdseye) was most common in the virgin forests of places as diverse as Michigan and West Virginia (Hough 1884, Sherwood 1936, Gagnon 1996). However, this may not have been as pronounced as inferred from the literature, but rather an issue of familiarity. For instance, the present-day concentration of birdseye in northeastern Canada, Michigan, Wisconsin, northern New England, and perhaps even the mid-Atlantic is partially a matter of awareness of the resource (Bragg 1995).

Perhaps the biggest uncertainty regarding the sustainability of the birdseye maple resource is the degree of genetic control associated with this grain abnormality. Some have speculated a genetic linkage (for example, Righter 1934), but this theory has never been adequately tested. If it is true, how has the last century of forest manipulation modified the sugar maple genetic pool? Has this phenotype been lost from much of its range, or is it still present, waiting for the right conditions to express it? We simply don't know.

The desire to retain this grain abnormality, especially if genetically controlled, favors the retention of some birdseye maples in the stand to help ensure these genes remain available. While this recommendation may sound counterintuitive to foresters and landowners striving to capture the value of this figured wood, many heavily figured birdseye maples are of such poor form and vigor that their current timber value is low. These cull maples are often removed to create growing space for future crop trees, but their long-term contribution to stand value may be better served by leaving them to ensure that their genetic material is retained.

Even with these concerns, there is little risk that birdseye will ever be completely eliminated. Birdseye maple is remarkably abundant in some contemporary large-scale reserves of old-growth northern hardwoods in Michigan and Wisconsin (Bragg and others 1997). Birdseye seems destined to become increasingly rare in managed northern hardwood landscapes (Bragg 2006). However, its value should still place it in the forefront of the management of many of these areas.

UPDATES TO THE BIRDSEYE ANNOTATED BIBLIOGRAPHY

The last annotated bibliography on birdseye figured grain (Bragg and Stokke 1999) was published almost a decade ago and scores of additional useful references have been found in the meantime (Appendix B). Many of these new citations were collected from sources such as the "Making of America" (http://quod.lib.umich.edu/m/moagrp/ and http://moa.cit.cornell.edu/moa/) online historical archives and Cornell University's "Core Historical Literature of Agriculture" (http://chla.library.cornell.edu/). Some internationally published abstracts of articles were identified in digital databases like AGRICOLA and TreeCD, and others came from the archives of the U.S. Forest Service's Forest Products Laboratory in Madison, WI.

Additionally, some references have been included as clarifications of ones cited in Bragg and Stokke (1999), either because they have been better identified or additional birdseye material related to that particular publication has surfaced. For example, the 1929 M.Y. Pillow references are identical in title and content to the Pillow (1930) citation provided in Bragg and Stokke (1999), the only distinction being that they were published in different outlets. However, references that only briefly note existing literature (for example, Cutter and others 2004) or merely mention the presence of birdseye in sugar maple are not included in this update.

ACKNOWLEDGMENTS

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Godman, R.M.; Erdmann, G.G. 1981. **Production of quality hardwoods.** In: [editor unknown]. Proceedings of the National Silviculture Workshop. Washington, DC: U.S. Department of Agriculture, Forest Service, Division of Timber Management: 152-162.

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MacLean, R. 1997. **Against the grain.** New Brunswick Telegraph Journal. November 3; Sect. A:1-2.

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Pickens, J.B.; Lee, A.; Lyon, G.W. 1992. **Optimal bucking of northern hardwoods.** Northern Journal of Applied Forestry. 9(4): 149-152.

Pillow, M.Y. 1930. **"Bird's eyes" in maple are not due to dormant buds.** Hardwood Record. 68: 45-46.

Pillow, M.Y. 1955. **Detection of figured wood in standing trees.** Report 2034. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 8 p.

Righter, F.L. 1934. **On the cause of birdseye maple.** Journal of Forestry. 32: 626-627.

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Sherwood, M.H. 1936. **From forest to furniture: The romance of wood.** New York, NY: W.W. Norton & Company, Inc. 284 p.

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Velling, P.; Vihera-Aarnio, A.; Hagqvist, R.; Lehto, J. 2000. **Valuable wood as a result of abnormal cambial activity—the case of *Betula pendula* var. carelica.** In: Savidge, R.; Barnett, J.; Napier, R. (eds.) Cell & molecular biology of wood formation. BIOS Scientific Publishers, Ltd.: Oxford, UK: 377-386.

APPENDIX A. TAXA IDENTIFIED AS POSSIBLY DEVELOPING BIRDSEYE OR BIRDSEYE-LIKE GRAIN ABNORMALITIES NOT REPORTED IN BRAGG AND STOKKE (1999)

Common name	Scientific name	Source reference (see Appendix B)
vine maple	*Acer circinnatum*	Ralph (1892)
Drummond's maple	*Acer rubrum* var. drummondii	Maxwell (1913)
rock maple	*Acer spicatum*	Brackett (1896)
tindalo	*Afzelia rhomboidea*	Goetz (1908)
red alder	*Alnus rubra*	Blackman (1998)
colonial-pine (or hoop-pine)	*Araucaria cunninghamii*	Anonymous (1895) Lincoln (1986)
revesa peroba	*Aspidosperma peroba*	Lincoln (1986)
birdseye calantas (or maranggo)	*Azadirachta integrifolia*	Timber Research and Development Association(1980) Lincoln (1986)
bird's-eye birch	*Betula verrucosa* f. oculosa *Betula pubescens* f. oculosa	Vaclav (1967)
Queensland-maple	*Flindersia brayleyana* *Flindersia pimenteliana* *Flindersia laevicarpa*	Cox (1949) Lincoln (1986)
British oak (or European oak)	*Quercus robur*	Laslett (1875) Cox (1949)
cypress	*Taxodium distichum*	Pelton (1961)
thuya (or thyine)	*Tetraclinis articulata* (syn. *Callitris quadrivalvis*)	Sherwood (1936) Cox (1949) Meiggs (1982) Lincoln (1986)
Pacific myrtle	*Umbellularia californica*	Cox (1949)
keyaki	*Zelkova serrata*	Lincoln (1986)

APPENDIX B. NEW ANNOTATED REFERENCES

1. Anonymous. 1810. Intelligence. The monthly anthology, and Boston review containing sketches and reports of philosophy, religion, history, arts, and manners (1803-1811). 8: 280-285. This article translates a French committee's take on the travels of "M. Michaux" (likely Andre Michaux) in the forests of the United States. Notes that the figured wood of maple was much sought after for cabinetmaking, and that tables of curly and birdseye maple have been sold at a "very high price". One of the earliest references that spells "birdseye" as it is now conventionally used.

2. Anonymous. 1832. Maine. The New-England Magazine. 2(5): 394-403. Author incorrectly states that birdseye and curly maple are almost exclusively the products of Maine's forests.

3. Anonymous. 1848. Queer fancies. Scientific American. 3(35): 275. Attributes an unnamed "late writer" with the recommendation that landscape painters be buried in a coffin built of birdseye maple to ensure the "fitness of things."

4. Anonymous. 1859. Ancient tables of wood. Scientific American. 14(41): 341. Describes how demand for birdseye maple in furniture has dropped drastically due to imitations using softwoods and stains. Birdseye maple has thus been relegated in many places to fuelwood.

5. Anonymous. 1874. The figure and color of wood. The Manufacturer and Builder. 6(10): 221. One of the earliest attempts to describe the formative mechanisms for several figured grains, including birdseye maple, which was attributed to "internal points or spines on the inside of the bark". Though the author is mistaken that these spines actually penetrate the wood and cause the indentations, the concept of bark-initiated indenting of the wood is close to current thinking (see Rioux and others 2003).

6. Anonymous. 1875. New way of cutting veneer. The Manufacturer and Builder. 7(2): 29. Details a "new" rotary cutting approach to veneer manufacturing by describing the yield of a 1,000 board foot birdseye maple log into 24,000 linear feet of veneer. More importantly, the article places a value of this figured log at $6 to $8 in 1875.

7. Anonymous. 1877. Glass veneers. The Manufacturer and Builder. 9(10): 223. Describes the process of mimicking natural birdseye maple using paint and glass. See Anonymous (1859) and Furuse and others (1994) for other means of imitating birdseye grain.

8. Anonymous. 1889. Notes. Garden and Forest. 2(81): 444. In a brief paragraph in this section of this journal, a "Professor Beal" (probably William James Beal of the Michigan State Agricultural College) is said to have found that birdseye is not found in trees less than 3 inches in stem diameter, nor higher in the crowns of even well-figured individuals. This brief report calls for the discovery of the developmental mechanism to aid in its commercial propagation.

9. Anonymous. 1895. Notes. Garden and Forest. 8(398): 410. The text cites a report from the Agricultural Gazette of New South Wales of a figure in colonial-pine (hoop-pine) (*Araucaria cunninghamii*) similar to birdseye maple.

10. Anonymous. 1905. Woodpeckers make birdseye maple, says a Maine man. The Washington Post (Washington, DC). July 23, 1905 edition, page ES8. A story written about an eccentric man from Patten, ME, named Greenleaf Davis, who worked for years to increase the density of woodpeckers near his home. Davis claims that these woodpeckers have pecked the maple trees on his property, causing them to produce birdseye. States that he had a hill near his camp with more than 300

birdseye maples that he planned to offer to the Audubon Society upon his death to sell and then donate the money for woodpecker protection. Davis was also featured in a later article by the Bangor, ME, correspondent of the Chicago Tribune and reprinted in the Washington Post in the July 7, 1907 issue (page M3).

11. Anonymous. 1908. Sugar maple. Silvical Leaflet 42. Washington, D.C.: U.S. Department of Agriculture, Forest Service. 4 p. States that the birdseye grain in sugar maple, highly prized in furniture construction, frequently results from the formation of dormant buds.

12. Anonymous. 1931. Pepper and salt. Wall Street Journal (New York, NY). October 17, 1931 edition, page 8. This feature provided (in addition to an ode to beer) a news item stating that Harvard University scientists had recently found trees buried in the tar sands near Edmonton, Alberta, Canada, of unidentified species that had "beautiful graining and coloring, the growth rings being clearly defined. It was a hard wood, with a deep, reddish color, and a grain resembling that of birdseye maple".

13. Anonymous. 1956. Tree and timber oddities. Southern Lumberman. 193(2417): 97. Attributes the formation of a birdseye-like grain abnormality in Norway birch burl to beetle larvae that tunnel into the wood, leaving a gallery that the tree eventually fills with darker colored cells. Calls this knowledge "…the only difference from birdseye maple."

14. Anonymous. 1997. Hardwood 'sinkers' salvaged to produce unusual lumber. Wood Technology. 124(8): 6. Recounts the story of the Superior Water-Logged Lumber Company (now Timeless Timber) of Ashland, WI, which salvages logs that had accidentally sunk decades ago in Lake Superior. Some of the most valuable of these logs are birdseye maple.

15. Baker, Frederick S. 1934. Theory and practice of silviculture. New York, NY: McGraw-Hill Book Company:291. Supports the assertion that birdseye maple arises from dormant buds.

16. Blackman, Ted. 1998. Use one load of logs to make eight loads of product. Wood Technology. 125(6):36-37. Notes birdseye in red alder (*Alnus rubra*).

17. Bozhok, A.A.; Vintoniv, I.S.; Ivaniv, O.S. 1985. Categories of decorativeness of the wood of sycamore growing in the Carpathians. Lesnoi-Zhurnal. 2: 117-119. This article reports on the occurrence of birdseye in sycamore maple (*Acer pseudoplatanus*) in the Russian Carpathian Mountains. According to the TreeCD abstract, the authors found birdseye sycamore maples had thin, platy bark with obvious indentations in the outer bark and leaves that fell later than non-birdseye individuals.

18. Brackett, Anna C. 1896. Among the trees. Harper's New Monthly Magazine. 93(556): 601-611. Mentions birdseye maple occurs in "rock maple," which, judging from the context, is not intended to be sugar maple. The author may have meant mountain maple (*Acer spicatum*).

19. Bragg, Don C. 1999. The birdseye figured grain in sugar maple (*Acer saccharum*): literature review, nomenclature, and structural characteristics. Canadian Journal of Forest Research. 29: 1637-1648. This review condensed most of what was known about birdseye at the time, from its geographic distribution to potential developmental mechanisms (including genetics) and describe its structural attributes by naming the obvious macrofeatures: the indentation (gelasinus), the protrusion (elatus), and the radial trace (vestigium). Four distinct varieties of birdseye maple are

identified: roundeye, fingernail, cat's paw, and distorted. Numerous pictures and references are provided.

20. Bragg, Don C. 2006. Potential contributions of figured wood to the practice of sustainable forestry. Journal of Sustainable Forestry. 23(3): 67-81. Provides a brief review of what is currently know about birdseye in sugar maple. Discusses birdseye maple and other figured grains as potential avenues to support specialized timber management regimes, including identification of the available resource, harvesting system adaptations, and improved recovery. Concludes with some thoughts on the sustainability of the current birdseye maple resource.

21. Bragg, Don C.; Stokke, Douglas D. 1999. An annotated bibliography on "birdseye" figured grain. Gen. Tech. Rep. NE-263. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 15 p. This paper reviews 96 sources of information on birdseye and birdseye-like grain abnormalities, including a list of other species thought to contain this figure type.

22. Brown, D.J. 1846. The trees of America; Native and foreign. New York, NY: Harper & Brothers: 82-83, 86. Brown's 1831 book on dendrology was abstracted in part by the journal The North American Review, including several mentions of birdseye. Reports birdseye to be "frequently exhibit[ed]" in "platanus-like" (sycamore) maple (*Acer pseudoplatanus*). Also lists "bird's-eye maple" as a common synonym for sugar maple in Britain and Anglo-America. Lists cabinets, bedsteads, writing desks, and inlays for bureaus and piano-fortes as key uses for the "accidental forms" of sugar maple, including curly and birdseye grains. Gives "Erable moucheté" as the French name of birdseye maple. Describes the size, appearance, and distribution of the birdseyes, and recommends tangential sawing to highlight the grain pattern.

23. Chovanec, D. 1992. 'Sleeping eyes'—a special feature of wood (Spiace ocka—zvlastna kresba dreva). Drevo. 47: 6, 150-152. This Slovakian publication with an English abstract apparently describes how birdseyes are identified, as well as some possible origins. Source identified using a TreeCD search.

24. Churchill, Edwin A. 2000. The painted furniture of Maine. Antiques. 157(5): 778-787. Describes some of the practice of painting furniture to appear as more valued species or figured grains, included birdseye maple.

25. Collingwood, G.H.; Brush, W.D. 1964. Knowing your trees. Washington, DC: American Forestry Association: 28-29. Describes how the "pebbled" appearance on the surface of boards sometimes leads to lodgepole pine (*Pinus contorta*) being labeled "bird's eye pine."

26. Cox, H.A. 1949. Wood specimens. London, UK: The Nema Press. 206 p. In addition to sugar maple and other true maples, this book also mentions birdseye in Queensland-maple (*Flindersia brayleyana*), thuya (*Tetraclinis articulate*), Pacific myrtle (*Umbellularia californica*), European oak (*Quercus robur*), and briar root (*Erica arborea*). Many of the pictured examples of birdseye in these species are more similar to burr or burl figures.

27. Doane, R.W.; Van Dyke, E.C.; Chamberlin, W.J.; Burke, H.E. 1936. Forest insects. New York, NY: McGraw-Hill Book Company: 392-393. This reference identifies a group of pitch midges (*Retinodiplosis inopsis*, the gouty pitch midge, and *Retinodiplosis resinicoloides*, the western pitch midge), whose boring into the wood of several pine species leads to a defect that causes the label of "bird's-eye pine" to be given to ponderosa pine (*Pinus ponderosa*).

28. Eyres, H.T. 1950. Introducing wood: Facts for all who handle it. London, UK: Sir Isaac Pitman & Sons: 40. Describes birdseye as at one time being popular paneling for yacht cabins. Dismisses the bird-peck theory of birdseye origin in favor of one suggesting that fungi retards radial growth, producing the grain pattern.

29. Forest Products Laboratory. 1929. Forest Products Laboratory research program 1929-1930. Unpublished report. Madison, WI: U.S. Department of Agriculture, Forest Service: 132, 134. This program description briefly describes a grafting study initiated by M.Y. Pillow intended to determine if scions of birdseye maple and figured walnut would work with ordinary root stock. This work almost certainly corresponds to Leopold's citation of a 1928 progress memo by Pillow and Bates.

30. Furnas, R.W. 1884. Reports on the forest condition and lumber and wood trade of western states and territories. In: Egleston, Nathaniel H. (ed.). Report on Forestry. Washington, DC: U.S. Department of Agriculture: 248. Notes "extraordinarily fine" birdseye in Oregon maple.

31. Furuse, Kyoko; Masuda, Minoru; Aota, Yoshiaki. 1994. Imitation of three dimensional glosses of wood by using micro-embossed lines—imitation of glosses of wavy grain figure and bird's eye figure. Journal of the Society of Materials Science, Japan. 43(485): 147-151. English abstract, text in Japanese. Mentions the emulation of birdseye grain using micro-embossed lines in a sheet of polyvinyl chloride.

32. Gayer, K. 1896. Schlich's manual of forestry. Volume V: Forest utilization (translated by W.R. Fisher from "Die Forstbenutzung"). London, UK: Bradbury, Agnew, & Co.: 65. Refers to birdseye maple as one type of burr, attributed to the extension production of dormant buds, which causes the fibers to abnormally twist around them.

33. Gibson, H.H. 1913. American forest trees. Chicago, IL: Hardwood Record: 428, 434-435, 440. The author reports birdseye occurs mostly in sugar maple, and less commonly, red and Oregon maples. Attributes birdseye formation to adventitious buds that fail to emerge, and reports a "pin-like core, resembling a fine thread, [that] connects the birdseye with the tree's pith". However, no such structure has been observed with microanatomical studies (see Rioux and others 2003).

34. Goetz, C.H. 1908. Structural characteristics of some Philippine woods. Forestry Quarterly. 6: 52-57. Mentions a birdseye figure in tinaldo (*Afzelia rhomboidea* or *Eperna rhomboidea*), a legume with good potential for cabinetmaking.

35. Harrar, E.S. 1958. Hough's encyclopedia of American woods, volume II. New York, NY: Robert Speller & Sons: 160-165. Briefly describes the commercial use of birdseye maple in modern stylings, including decorative panels.

36. Hopkins, A.D. 1894. The woodpecker and bird's-eye poplar. Garden and Forest. 7(343): 373. Attributes a birdseye-like grain abnormality in yellow-poplar to damage from woodpeckers, but is not sure if this mechanism is responsible for birdseye maple (although he implies the link due to downy woodpecker's fondness for sugar maple sap).

37. Hough, Franklin B. 1884a. Report on the forest conditions and lumber and wood trade of New Hampshire and West Virginia. In: Egleston, Nathaniel H. (ed.). Report on forestry. Washington, DC: U.S. Department of Agriculture: 379, 387. Mentions that birdseye is found in the sugar

maple of West Virginia, and reports "large lots" of black walnut and figured maple in the headwaters of streams such as the New River.

38. Hough, Franklin B. 1884b. Report on the production of maple sugar in the United States and Canada. In: Egleston, Nathaniel H. (ed.). Report on forestry. Washington, DC: U.S. Department of Agriculture: 406. In a brief section describing the wood of sugar maple, Hough mentions that he knew of $1,000 being paid for a single birdseye maple tree.

39. Hough, Romeyn B.; Leistikow, Klaus Ulrich. 1888. The American woods: exhibited by actual specimens and with copious explanatory text, part I. Lowville, NY: Romeyn Hough: plate 7b. In this self-published collection, Hough and Ulrich classified birdseye (which they also called "pin maple") and "blister maple" as a species (*Acer saccharinum*) distinct from straight-grained sugar maple (*Acer saccharum*). *Acer saccharinum* is currently the accepted scientific name for silver maple. The authors also provide German ("Augen Ahorn"), French ("Erable oeil d'oiseau"), and Spanish ("Arce ojo de paxaro") names for birdseye maple.

40. Hubert, Ernest E. 1931. An outline of forest pathology. New York, NY: John Wiley & Sons, Inc.:12-14. Brief reference interesting primarily in that it lists birdseye as a tree disease resulting from stimuli related to a "chemical unbalance within the plant or from an unbalancing of physiological or environmental factors".

41. Johnson, Tim. 2000. Birdseye maple. American Woodworker. 81: 28-29. Provides advice for procuring and woodworking with birdseye maple.

42. Kellogg, R.S. 1914. Lumber and its uses. Chicago, IL: The Radford Architectural Company: 115, 117, 180, 276. Suggests that for birdseye maple, the use of "two thin coats of pure grain alcohol white shellac evenly applied directly on the wood…sandpapering thoroughly each coat… [and] waxing…will give splendid results." Notes that birdseye and curly maple are often used to construct harp boxes.

43. Koehler, Arthur. 1926. Identification of furniture woods. Miscellaneous Circular 66. Washington, DC: U.S. Department of Agriculture:19. Although the author does not attribute a specific cause of birdseye, he states that birdseye differs from burl in not having a pith associated with a bud. Also states that birdseye occurs almost exclusively in a small percentage of maple.

44. Kormanik, Paul P.; Brown, Claud L. 1967. Adventitious buds on mature trees. Research Note SE-82. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 7 p. While this note never mentions birdseye, the grain patterns shown related to adventitious buds look similar in many ways to birdseye maple. However, the pith apparent in bud traces is a distinguishing characteristic not found in birdseye.

45. Laslett, Thomas. 1875. Timber and timber trees, native and foreign. London, UK: Macmillan and Co.: 53. Identified a figure in British oak (*Quercus robur*) that resembles birdseye maple.

46. Leopold, Aldo. 1929. Some thoughts on forest genetics. Journal of Forestry. 27: 708-713. Briefly speculates on the roles of genetics and site conditions on birdseye formation, including the mention of an attempt by M.Y. Pillow and C.G. Bates in 1928 to breed birdseye maple. To date, this memo had not been uncovered, but Leopold cites it as: Pillow, M.Y.; Bates, C.G. 1928. Bird's-eye maple study, memorandum of progress in 1928, June, 1928. Forest Products Laboratory and Lake States Forest Experiment Station.

47. Lincoln, William A. 1986. World woods in colors. New York, NY: Macmillan Publishing Company. 320 p. Identifies a number of species with birdseye or birdseye-like grain abnormalities, including hoop-pine (*Araucaria cunninghamii*), revesa peroba (*Aspidosperma peroba*), birdseye calantas (*Azadirachta integrifolia*), ponderosa pine (*Pinus ponderosa*), Queensland-maple (*Flindersia brayleyana*, *Flindersia pimenteliana*, and/or *Flindersia laevicarpa*), thuya (*Tetraclinis articulate*), and keyaki (*Zelkova serrata*).

48. MacLean, Rick. 1997. Against the grain. New Brunswick Telegraph Journal: A1-A2. November 3, 1997. Describes the problem New Brunswick's crown forests are having with the theft of birdseye—an estimated 80 percent of the hundreds of timber theft cases annually reported during this period involved birdseye. A number of legal cases are cited, including the penalties involved. The act of cutting out a piece of bark to examine the bole for birdseye maple (xylemic examination) is called "prospecting".

49. MacLean, Rick. 1997. DNA tests could be a weapon in helping catch tree rustlers. New Brunswick Telegraph Journal: A1. November 4, 1997. Suggests the use of DNA testing to help identify stolen timber, including birdseye maple logs, but notes the lack of funding to develop the techniques required.

50. Maxwell, Hu. 1913. Uses of the commercial woods of the United States. Beech, birches, and maples. Bull. 12. Washington, D.C.: U.S. Department of Agriculture: 34, 38-39, 41-42, 49, 53. This monograph describes a number of species with birdseye, including sugar maple, bigleaf maple, and Drummond's maple (*Acer rubrum* var. drummondii). The Drummond's maple reference identifies a "peculiarly fine class" of birdseye from the lower Red River in Louisiana that was used for gunstocks and violins. Other uses listed by the author for birdseye included furniture, pianos, harps, and veneer. Maxwell favors the dormant bud theory of birdseye formation.

51. McCabe, Carol. 2003. Figured woods. Early American Life. 34(2): 50-55. An article on the use of figured wood in furniture by early American craftsman. Repeats most conventional theories on birdseye formation without favoring any in particular. Also mentioned some "folk wisdom" repeated by Lou Irion that some "old-timers" believed birdseye was caused by the rocking of cold trees in the wind. Notes the use of birdseye in a Portsmouth Federal-style chest of drawers and a Sheraton sewing table, both circa 1810, as well as by more modern designers.

52. Meiggs, Russell. 1982. Trees and timber in the ancient Mediterranean world. Oxford, UK: Clarendon Press. 553 p. Discusses the use of figured woods by the ancient Greeks and Romans for furniture, especially tables. Mentions "citrus-wood" (*Callitris quadrivalvis*, synonymous with *Tetraclinis articulata*) and unspecified maples (*Acer* spp.) as producing birdseye-like figure.

53. Patterson, Douglas. 1988. Commercial timbers of the world, 5th ed. Brookfield, VT: Gower Technical Press: 177. Attributes birdseye in sugar maple to an insect attack.

54. Pelton, B.W. 1961. Furniture making and cabinet work: a handbook. Princeton, NJ: D. Van Nostrand Company, Inc.: 475. Suggests applying a thin coat of walnut stain, followed by shellac, gloss varnish, and dull varnish for "bird's-eye or curly grain cypress" (i.e., baldcypress, *Taxodium distichum*).

55. Pillow, M.Y. 1929a. "Bird's eyes" in maple are not due to dormant buds. Wood Working Industries. 6(3): [number of pages not given]. Identical to Pillow (1930) reference in Bragg and Stokke (1999).

56. Pillow, M.Y. 1929b. "Bird's eyes" in maple are not due to dormant buds. Furniture Manufacturer. 38(6): 106, 108. Identical to Pillow (1930) reference in Bragg and Stokke (1999).

57. Powell, G.W. 1879. American forests. Harper's New Monthly Magazine. 59(351): 371-374. Author decries the loss of birdseye maple and other figured grains destroyed by slash-and-burn agriculture in pioneer America.

58. Ralph, Julian. 1892. Canada's El Dorado. Harper's New Monthly Magazine. 84(500): 171-189. Identifies a figure closely resembling birdseye in vine maple (*Acer circinnatum*) along the coast of British Columbia.

59. Rioux, D.; Simard, M.; Rheault, F.J.; Lessard, G. 1997. Fine anatomy of birdseye sugar maple. In:CTIA/IUFRO International Wood Quality Workshop. Quebec City, Canada: Forintek: IX-17. This abstract describes preliminary anatomical work conducted by the authors that eventually is published in much greater detail in Rioux and others (2003). See also Rioux and others (1999).

60. Rioux, D.; Yamada, T.; Simard, M.; Lessard, G.; Rheault, F.J.; Blouin, D. 2003. Contribution to the fine anatomy and histochemistry of birdseye sugar maple. Canadian Journal of Forest Research. 33: 946-958. The most detailed anatomical and biochemical assessment of the birdseye grain in sugar maple published to date. Using light and transmission electron microscopes, this seminal publication identified numerous physiological properties of birdseye, including inclined axial elements, shorter and smaller vessels, occasional gaps between xylem cells, abnormal secondary wall thickenings in vessels, and an absence of multiseriate rays. The authors reported no evidence of pith or dormant buds in their examinations. Collapsed and hypertrophied cells were observed, indicating cambial initial injuries arising from the pressure exerted by inner bark fibers. Abnormalities also appeared in the phloem and rays. Contains many detailed micrographs identifying key deformations and differences with normal sugar maple wood.

61. Rioux, D.; Yamada, T.; Simard, M.; Lessard, G.; Rheault, F.J.; Blouin, D. 1999. Anatomy and cytochemistry of birdseye sugar maple. Canadian Journal of Plant Pathology. 21: 204-205. This abstract expands upon the work of Rioux and others (1997) by including cytochemical work indicating that birdseyes are less lignified than normal xylem. As with Rioux and others (1997), this work is extensively updated in Rioux and others (2003).

62. Roth, Filibert. 1895. Timber: An elementary discussion of the characteristics and properties of wood. Washington, D.C.: Government Printing Office:11, 23. Lists birdseye panels in ship saloons and palace cars. Associates the small (less than 1/8 inch) eyes with dormant buds and labels the expression of this structure in the wood as "landscape".

63. Sargent, C.S. 1885. Woods of the United States. New York, NY: D. Appleton and Company: 20, 22. Mentions birdseye grain in bigleaf and sugar maple, and notes the "accidental forms [curly and birdseye maple]… are common and highly prized".

64. Sherwood, Malcolm H. 1936. From forest to furniture. New York: W.W. Norton & Company: 45-49, 95, 110, 115, 213. This citation is an expansion of the original provided in Bragg and Stokke (1999). Four additional references to birdseye or birdseye-like figured grains were found in this text, including reference to good birdseye maple being used as an economical substitute for different burls, and how similar-looking thuya (*Tetraclinis articulata*) burlwood is to birdseye maple. This reference may have served as the source for the factoid reported in Anonymous (1956)

about the origin of a birdseye-like grain abnormality in Norway birch, attributed to tunneling beetle larvae.

65. Stone, Herbert. 1904. The timbers of commerce and their identification. London, UK: William Rider & Son, Ltd.: xvii, 55, 58, 260 (Plate XX). Holds that birdseye maple arises from an insect attack. Includes "bird's-eye maple" as a common alternative name for sugar maple. Reports that Oregon maple's birdseye figure is "very beautiful". This reference also contains two pictures of birdseye maple, with a caption labeled "the worm-eaten [b]ark, showing the origin of the figure".

66. Timber Research and Development Association. 1980. Timbers of the world, volume 2. Lancaster, UK: The Construction Press, Ltd.: 26. Describes a "birdseye calantas" (also called maranggo in the Philippines) found in *Azadirachta integrifolia*.

67. Vaclav, E. 1967. Bird's-eye birch and flamy birch, two important forms of birch. Sbornik-Vedeckeho, Lesnickeho Ustavu Vysoke Skoly Zemedelske v Praze. 10: 117-136. TreeCD describes this work as illustrated. The author identifies two technical forms (f.), *f. oculosa* (birdseye) and *f. flammifera* (flamy) in *Betula verrucosa* (silver birch) and distinguishes *f. oculosa* from *f. carelica*. Also lists *f. oculosa* as occurring in *Betula pubescens* (European white birch).

68. Vaclav, E.; Kucera, B.; Rezabkova, J. 1971. The anatomical, physical and mechanical characteristics and properties of the wood of curly, bird's-eye and flamy birch. Sbornik-Vedeckeho, Lesnickeho Ustavu Vysoke Skoly Zemedelske v Praze. 12: 111-127. TreeCD lists this as a "more detailed" version of a previous article.

69. Van Goethem, Larry. 1996. "Common sense" guides Upper Michigan logger. The Northern Logger & Timber Processor. 44(11): 12-14. Describes some of the life of logger Jeff Carlson, including his skills in finding, cutting, and selling birdseye maples. Mentions interest by a timber buyer for a Japanese cello-maker looking for the "finest quality" birdseye maple logs.

70. Vaughan, Melville M. 1896. A California principality: Humboldt and its redwoods. Overland Monthly and Out West Magazine. 28(165): 328-368. Stated that redwoods developed "immense bird's eye burls".

71. Velling, P.; Viherä-Aarnio, A.; Hagqvist, R.; Lehto, J. 2000. Valuable wood as a result of abnormal cambial activity—the case of *Betula pendula* var. *carelica*. In: Savidge, R.A.; Barnett, J.R.; and Napier, R. (eds.). Cell and molecular biology of wood formation. Oxford, UK: BIOS Scientific Publishing, Ltd.: 378. Holds that visually similar figured grains like curly birch and birdseye maple have different developmental mechanisms.

72. Walck, Christa; Strong, Kelly C. 2001. Using Aldo Leopold's land ethic to read environmental history: The case of the Keweenaw forest. Organization & Environment. 14(3): 261-289. Mentions that birdseye maples from the Keweenaw Peninsula in northern Michigan were the most highly valued of all maples. They quote a manager of a local timber company reporting stumpage prices of between $5,000 and $50,000 per 1,000 board feet, or up to $25,000 for an individual tree.

73. Walters, Brady. 1995. Birdseye prized: high demand means Keweenaw commodity more rare, valuable. The Daily Mining Gazette (Houghton, MI). Tuesday, May 2, 1995 edition, page 1B. Reviewed research on birdseye maple at Michigan Technological University. Interviewed several

individuals involved with the birdseye maple trade in the Upper Peninsula of Michigan, and reported the theft of birdseye logs by helicopter.

74. Weck, Johannes. 1966. Dictionary of forestry. Amsterdam: Elsevier Publishing Company: 154, 246. Provides the German (Maserholz), French (bois m madré), Spanish (madera f veteada), and Russian (свилеватая древесина) terms for "bird's eye". Also lists the following names for birdseye: Vogelaugenmaser (German), madrure f en oeil de perdrix (French), veteado m de ojo de perdiz (Spanish), and узор m "птичий глаз" (Russian).

75. Weyerhaeuser Company. 1956. Characteristics of modern woods. 6th ed. Tacoma, WA: Weyerhaeuser Company, Wood Products Division: 38. Provides a listing for birdseye maple, a rare occurrence most commonly found in sugar maple. Describes the distribution of birdseye in a stand as unpredictable, and notes that some trees with birdseye have it only as patches or stripes irregularly distributed along the bole.

76. White, Marshall S. 1980. Wood identification handbook: commercial woods of the United States. New York, NY: Charles Scribner's Sons: 55-56. Reports that birdseye can be seen in the bark of sugar maple logs and is "eagerly" sought by log buyers, who turn these figured logs into veneers often 1/64th of an inch thick (or less).

77. Williams, E. 1991. Tug Hill, a threatened paradise. Conservationist. 45(5): 2-7. The author claims that for a couple of decades during the middle of the 19th Century, two-thirds of all of the birdseye maple veneer produced in the world came from the Tug Hill Plateau in New York.

78. Wiman, Erastus. 1889. The greater half of the continent. North American Review. 148(386): 54-73. The author claims that Canadian forests contain "enormous supplies" of birdseye maple.

79. Zuikhina, S.P. 1975. Abnormal structure of the wood in *Acer pseudoplatanus* in the Carpathians. Probl. Onkol. I Teratol. Rastenii. [no volume listed]: 191-193. This Russian-language account, abstracted in TreeCD, mentions birdseye as one of the figured grains of sycamore maple studied in plantations. States that birdseye maples, occurring in 10 percent of trees considered, are distinguishable by the fine pitting of the bark's surface. Abstract information is very similar to another work credited by TreeCD to Zuikhina in 1976 and may prove to be the same material.

80. Zuikhina, S.P. 1976. Anomalous structure of sycamore (*Acer pseudoplatanus*) wood in the Carpathians (Abomal'noe stroenie drevesiny klena belogo v Karpatakh). Probl. Onkol. I Teratol. Rastenii. [no volume listed]: 191-193. See Zuikhina (1975) entry.

THE AMISH FURNITURE CLUSTER IN OHIO: COMPETITIVE FACTORS AND WOOD USE ESTIMATES

Matthew Bumgardner, Robert Romig, and William Luppold[1]

Abstract.—This paper is an assessment of wood use by the Amish furniture cluster located in northeastern Ohio. The paper also highlights the competitive and demographic factors that have enabled cluster growth and new business formation in a time of declining market share for the overall U.S. furniture industry. Several secondary information sources and discussions with local manufacturers were utilized. Wood use for the cluster was estimated at 44 million board feet per year, a volume equivalent to 11 percent of the total volume of hardwood lumber produced in Ohio or 19 percent of the hardwood lumber used in appearance-based applications in the State. Although the Amish firms are highly concentrated within the Holmes County region, the typical firm is small in size (median of four employees). As the overall furniture manufacturing sector in the United States continues to struggle with imports, the Amish segment likely will become an increasingly important market for hardwood lumber, both regionally and nationally. However, the large number of small firms can create distributional challenges for suppliers.

INTRODUCTION

Amish Furniture Manufacturing

The Amish traditionally have undertaken agriculture-related occupations (Stinner and others 1989); however, as farmland has become increasingly scarce and expensive, and as the Amish population has grown, more are seeking opportunities in nonfarming occupations such as manufacturing (Lowery and Noble 2000). Amish-made furniture is an example of an emerging manufacturing sector.

Holmes County, Ohio, is the largest Amish settlement in the world; the Amish comprise nearly half of the county's total population (Lowery and Noble 2000), which was estimated at 38,943 in 2000 (USDC Census Bureau 2007). In 1973, only 3 percent of Amish heads of households in Holmes County were employed in the secondary wood sector; by 1997, this percentage had increased to 14 percent. These are likely conservative estimates as several furniture manufacturers were included in a broader manufacturing category. When general manufacturing is combined with primary and secondary wood manufacturing, 34 percent of the heads of household in Holmes County were employed in these sectors in 1997, up from 16 percent in 1973 (Table 1). Agriculture-related occupations declined from 48 percent to 21 percent of Amish occupations in the county over the same period (Lowery and Noble 2000).

The Amish furniture sector employs many aspects of competitiveness frequently listed as critical for the survival of domestic manufacturers (Bumgardner and others 2004, Buehlmann and others 2006). Amish furniture often is associated with quality craftsmanship and solid wood construction. The Amish name serves as a domestic brand name with wide familiarity among consumers. There are dedicated Amish-made furniture retail stores located throughout the United States (Amish.Net n.d.). In most of these stores, semi-customization is possible, allowing customers to choose from different species, finishes, and hardware

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Table 1.—Amish employment in selected occupational sectors in Holmes County, Ohio, 1973 and 1997 (Lowery and Noble 2000)

Sector, 1973	%	Sector, 1997	%
Agriculture	48	Agriculture	21
Manufacturing	10	Manufacturing	15
Secondary Wood	3	Secondary Wood	14
Primary Wood	3	Primary Wood	5

for a given piece and design. The products often are locally or regionally sourced and thus the customized requests are available with relatively short lead times.

Competitive Factors of the Ohio Cluster

Aspects of "clustering" are present with the concentration of Amish furniture manufacturers in Holmes County. Clusters can be defined as industries (manufacturers, suppliers, services, etc.) related to the same product existing in close proximity. Clusters often include research and educational institutions, consultants, etc. that help support the core industry. Clusters can be characterized as having well developed supply chains, wide use of current technology, and intense competition among local firms (Schuler and Buehlmann 2003). In spite of the local competition, each cluster element reinforces the others and helps create a competitive advantage for all. For the Amish, competition is tempered by a sense of cooperation (National Hardwood Lumber Association 2007). With furniture, cooperation can come from joint design and production of an entire furniture collection by individual manufacturers that focus on specific pieces such as chairs or tables.

An example of a competitive advantage arising from furniture clustering in Holmes County is Ohio Certified Stains, maintained by a group of manufacturers that has worked with local suppliers to establish a collection of standardized stains. Each color within the system matches if bought from a participating supplier (Anonymous 2005, p.9). Another example of clustering is found in distribution, as many of the dedicated Amish retail stores are located near the manufacturing centers in Pennsylvania, Ohio, and Indiana (Amish.Net n.d.). Porter (1998) claims that cluster effects can extend downstream to channels and customers; that is, distribution becomes part of the cluster and can generate competitive advantage. The Amish clusters of manufacturing and retail are proximate to several major population centers, and thus potential markets. This is in contrast to other notable competitive furniture clusters (e.g., northern Italy and Denmark), where most of the production is export oriented (Schuler and Buehlmann 2003). To date, most consumption of Amish-made furniture has been domestic, although interest in exporting is growing. Conversations with local manufacturers suggest distribution from the Holmes County cluster reaches nearly all 50 states.

OBJECTIVE

As the domestic furniture manufacturing industry continues to decline as a market for hardwood lumber, the Amish-based sector is positioned to become an increasingly important component. Little is known about the size of this industry segment or its impact on regional or national hardwood lumber demand. This study is a preliminary assessment of wood use by Ohio's Amish furniture cluster.

METHODS

Determining the Number of Firms

Data were collected from the 2005-2006 edition of "The Furniture Book: A Complete Guide to the Furniture Manufacturers and Wholesalers in Ohio's Amish Country" (Anonymous 2005). This guide (hereafter, referred to as The Furniture Book) covers all known Amish establishments in Holmes County, Ohio, and portions of five surrounding counties, measuring roughly 1000 sq. miles in area. Further, a meeting was held with four representatives from three Amish furniture manufacturers in Holmes County to discuss the project and the assumptions made in determining wood use estimates. These firms were larger in size and older in establishment age than the average Holmes County Amish furniture firm.

Each of the nearly 600 entries in The Furniture Book was analyzed. Data of interest included number of employees, year of establishment, and product descriptions. A total of 153 entries were removed from the list; those removed consisted primarily of finishing and distribution firms, as well as manufacturers of lawn/outdoor furniture, bedding, upholstery, and crafts. Thus, 429 establishments were identified as manufacturers of household furniture, components, and related products[2]. Discussions with the local manufacturers indicated that a few firms listed in The Furniture Book had gone out of business; conversely, a few existing firms were not listed. Consequently, the figures reported above reflect adjustments for unlisted firms and for those no longer in business.

As a cross-reference to the listings in The Furniture Book, the "Secondary Directory of Ohio Wood Manufacturing Companies, 2002" (Romig and others 2002), a directory compiled by Ohio State University and the Ohio Department of Natural Resources, was analyzed (referred to hereafter as the Directory). For Holmes County, 80 firms were listed that produced household furniture and related products. Of those, 67 firms, or 84 percent, also were listed in The Furniture Book. This cross-listing suggests general agreement between the sources, although it is apparent that the number of listings in The Furniture Book was much larger than those in the Directory.

Determining Employment and Wood Use Figures

Employment data were available from The Furniture Book for 271 of the firms. For the 158 firms not reporting number of employees (including a small number added through discussion with local manufacturers but with unknown employment information), data were imputed. It was noted that many firms advertised in The Furniture Book. For firms with one, two, or three employees, the advertisement rate was about 25 percent. For firms with four employees, this figure jumped to near 50 percent, and was more than 80 percent for firms with five employees. Very few of the firms with missing employment data were advertisers, so it was assumed that these firms tended to be small. These firms therefore were assigned employment values of one, two, or three employees in proportion to the prevalence of these figures among reporting firms. Given that the overall employment mean for reporting firms was 7.3 and the median was 4.0 (discussed more in the Results section), these estimates seemed reasonable.

The cross-reference with the Directory provided employment figures for six nonreporting firms in The Furniture Book. For these firms, assigned employment (as described above) was replaced with the figure

[2]Related products included items such as grandfather clocks, porch swings (if specified as being made from hardwoods), jewelry cabinets, log furniture, mirrors, and fireplace mantels. There also were some millwork and cabinet products. Such products were only occasionally listed compared to household furniture products.

Table 2.—Number of firms and employees, median firm size, and median year of establishment for furniture manufacturers, finishers, and wholesale distributors in Ohio's Amish furniture cluster

Firm type	Number of firms	Total employment[1]	Employees per firm[2]	Year established[2]
Manufacturers	429	2,723	4.0	1996.0
Finishers	50	197	4.0	2000.0
Wholesale Distributors	13	71	5.5	1997.0

[1] Based on the sum of reported (various sources) and assigned employment.
[2] Based on reporting firms only (Anonymous 2005).

reported in the Directory. The range in reported employment for these firms was 8-65, somewhat higher than the assigned values (range 1-3). While it was believed that most nonreporting firms were small, obviously some were larger companies. Also, discussion with local manufacturers provided estimates for 26 additional Furniture Book entries with missing employment data, and again these tended to be higher than the imputed values.

Once a total number of employees was established, this figure was multiplied by an estimate of hardwood lumber use per employee. Employment in the wood household furniture industry, according to U.S. Department of Labor (USDL) data (USDL Bureau of Labor Statistics 2006), was divided by hardwood lumber use by the furniture industry, according to the Hardwood Market Report (2004, 2005, 2006) for the 5-year period of 2000-2004 (the latest year for which hardwood lumber use data were available). Using this method, we estimated the average wood use per employee over the period to be 17,433 board feet (bf) per year; discussion with local manufacturers suggested this was a reasonable estimate. When we considered the appropriateness of this ratio, the generally small and sometimes less mechanized nature of Amish firms must be balanced with the fact that most Amish furniture is constructed of nearly all solid wood, which is uncommon in the broader domestic furniture industry.

RESULTS

Firm Size and Establishment

Ohio Amish furniture manufacturers employed a median of 4.0 employees in 2005; the median year of establishment was 1996 (Table 2). These figures suggest that the typical Amish furniture manufacturer in Ohio is small and relatively new. The number of employees ranged from 1 to 105. Figure 1 shows the distribution of firm size (including reported and imputed values), with an obvious skew to the right. The small size of the typical Amish firm is countered by the sheer number of establishments: 429 firms in an approximately 1000-sq.-mile area, or roughly the size of two counties in Ohio.

The 1990s generally were favorable times for the overall domestic furniture industry, as shipments increased in real terms (constant 1982 dollars) from $6.3 billion in 1990 to $7.7 billion in 1999 (Luppold and Bumgardner, in press). Many Amish producers in Ohio entered the market around this time, based on the median establishment age of 1996. As shown in Figure 2, a plurality of the Amish firms present in 2005 was established in 1999, which also was the peak year for value of domestic furniture shipments. Since 1999, furniture imports have increasingly captured market share from domestic manufacturers; it seems this rise in imports negatively influenced the establishment rate of Amish furniture firms as well. On the other hand, 27 percent of the Amish furniture manufacturers operating in Ohio in 2005 were established since 2000. Porter (1998) claims that it takes about a decade for a cluster to establish depth and to realize a competitive advantage; from Figure 2 it seems that the majority of firms were established between 1989

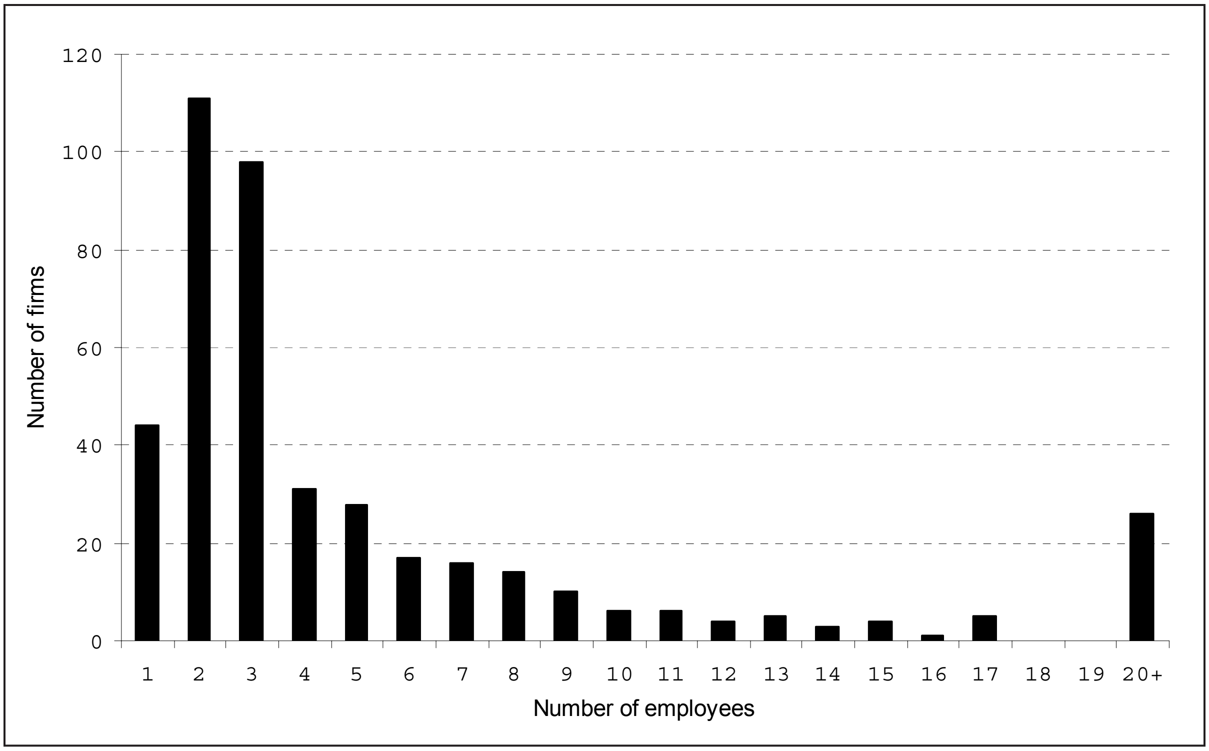

Figure 1.—Distribution of establishment size for Amish furniture manufacturers in Ohio's Holmes County cluster (various sources).

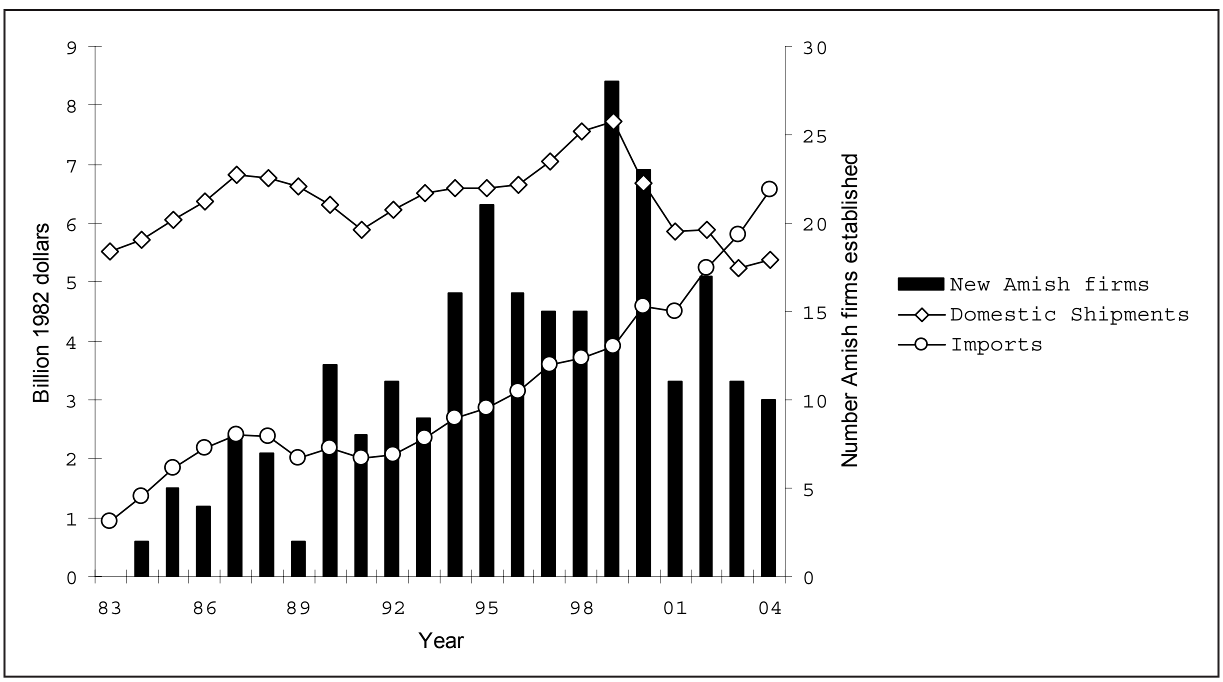

Figure 2.—Value of overall domestic wood household furniture shipments and imports by year (Luppold and Bumgardner, in press), and year of establishment for Ohio Amish furniture manufacturers in operation in 2005 (Anonymous 2005).

and 1999 and thus the cluster is maturing. In sum, it seems that the Amish furniture cluster in Holmes County arose from an economic transition away from locally oriented agricultural occupations, due in part to an increasing population and decreasing land base for farming. As such, it increasingly operates within the parameters of the broader U.S. economy.

Employment and Wood Use

The total number of employees of reporting firms was 1,959; the total number of employees including assigned employment was 2,723 (Table 2). However, these figures included some known component manufacturers that supplied local furniture manufacturers. Their inclusion would inflate wood use estimates since the same wood would be double-counted—once for the employee at the component firm and once for the employee at the furniture firm. Discussion with local manufacturers identified several such firms, which were removed for generation of wood use estimates. The adjusted figures were 1,911 employees for reporting firms and 2,497 employees including assigned estimates. The latter figure, multiplied by the average consumption per employee for the overall furniture industry (17,433 bf) results in hardwood lumber use of 43,530,201 bf annually by the Ohio Amish furniture cluster.

As Ohio was listed by the USDC Census Bureau (2006) as producing 401 million bf (mmbf) of hardwood lumber in 2005, these results suggest that the Amish furniture industry consumes the equivalent of about 11 percent of the hardwood lumber produced in Ohio. Including only appearance-based uses (58 percent of total production excluding pallets and railway ties) (Hardwood Market Report 2006) results in consumption of the equivalent of nearly 19 percent of Ohio's grade lumber.

New Business Development in the Cluster

Data also were available in The Furniture Book for service providers in the cluster, including finishing and wholesale distribution. Fifty finishing establishments were listed. The median number of employees per firm was 4.0. Median year of establishment was 2000 (Table 2). These results suggest that the finishing portion of the cluster was established later than (i.e., as a result of) the manufacturing portion, and that these firms are similar in size to the manufacturers. New business formation is a characteristic of successful clusters, and increases the collective pool of competitive resources that gives companies in the cluster competitive advantage over firms in other locations (Porter 1998). The sum of employees by reporting finishing firms was 124. When we assigned to those with missing employment data the mean/median of 4.0 (very few finishers advertised, so there was no basis for assigning employment; range in reported employment was just 1 to 10), there were 197 employees in wholesale finishing in Ohio's Amish furniture cluster.

For wholesale distributors, 13 establishments were listed. Of these, 10 provided employment and year of establishment data. The median number of employees per firm was 5.5. Median year of establishment was 1997 (Table 2). Similar to finishing firms, these results suggest that the distribution portion of the cluster was established slightly later than the manufacturing firms (e.g., new business formation), and they are similar in size to the manufacturers and finishers. The sum of employees by reporting firms was 62. To assign employment figures to firms with missing values, it was noted that the rate of advertising went up substantially for firms with greater than three employees; since none of the firms with missing values advertised, an employment number of 3 was assigned to the four missing values. As the range in employment among the distribution firms with known values was 3 to 14, this seemed like a suitable estimate. As a result, there are an estimated 71 employees in wholesale distribution in Ohio's Amish furniture cluster, although a majority of distribution employment is non-Amish as indicated through discussion with local manufacturers.

DISCUSSION

When wood household furniture manufacturers, finishers, and distributors, are combined, approximately 2,991 persons are estimated to be employed in Ohio's Amish furniture cluster, excluding a small number of lawn/outdoor furniture, bedding, upholstery, and crafts manufacturers, as well as other suppliers and service providers in the cluster. This employment corresponds to nearly 500 establishments in an approximately 1000-sq.-mile area. In sum, it is a concentrated cluster of many small firms. This cluster reasonably could be consuming about 44 mmbf of hardwood lumber per year, or the equivalent of about 11 percent of Ohio's total hardwood lumber output and 19 percent of the hardwood lumber used in appearance-based applications in Ohio.

As the Amish furniture manufacturing and distribution model seems to employ many of the competitiveness factors discussed in the literature, and has fared relatively well during a very volatile period in domestic manufacturing, this segment likely will continue to be an important regional market for hardwood lumber. Perhaps similar conditions exist in other areas with Amish concentrations (e.g., portions of Pennsylvania and Indiana). Collectively, Amish furniture manufacturing could be having a measurable impact on U.S. hardwood lumber demand. However, the small size and numerous manufacturers in these clusters can create distribution challenges for suppliers. For example, portions of one load of lumber may be delivered to multiple firms, each with different specifications and products. Perhaps this is one reason why investment in lumber sorting technologies is a priority for hardwood sawmills (Buehlmann and others 2007).

Can the Amish furniture model work elsewhere in the United States? Portions seemingly could be implemented (e.g., development of supply chains that can offer semi-customized pieces, more emphasis on brand image); however, other features might be more difficult to replicate, such as the cooperative aspects of the society and the commitment to furniture manufacturing as a way of life as farming becomes less viable. Firms operating within the Amish cluster are positioned to take advantage of niche opportunities by cooperating with others to source components and services not easily produced in-house, especially given their typically small size. The clustering dynamic thus seems paramount to the success of the Amish model, even as firms seek to be individually profitable.

Study Limitations

The majority of firms and associated data used in this analysis came from The Furniture Book. However, the figures used in this paper include both reported and assigned employment numbers, and other secondary data sources were utilized. The procedures also were discussed with local manufacturers, which resulted in changes to some employment assignments and firms included in the analysis. The firms included in the wood use analysis likely included some that produce components supplied to local furniture manufacturers, so wood-use estimates might be slightly inflated. Although all known components firms that supplied local firms exclusively were removed from the analysis, some could have been missed and some supplied a combination of local and nonlocal secondary manufacturers. Lastly, although the terminology used throughout the report used the name "Amish" to describe all firms, some were non-Amish owned but located within the cluster. Discussion with local manufacturers suggested the non-Amish proportion was about 15 percent, but even among these firms most employees were Amish. It also should be noted that the "furniture" terminology used throughout the paper included some cabinet and millwork firms, but this proportion was small.

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STRESS WAVE VELOCITY AND DYNAMIC MODULUS OF ELASTICITY OF YELLOW-POPLAR RANGING FROM 100 TO 10 PERCENT MOISTURE CONTENT

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Abstract.—Moisture content has a significant impact on mechanical properties of wood. In recent years, stress wave velocity has been used as an in situ and non-destructive method for determining the stiffness of wooden elements. The objective of this study was to determine what effect moisture content has on stress wave velocity and dynamic modulus of elasticity. Results indicated significant relationships between moisture content and average wave time. This study suggests that increasing moisture content reduces stress wave velocity and needs to be considered when performing non-destructive evaluations using stress wave velocity.

INTRODUCTION

Research concerning the mechanical properties of solid wood indicated that modulus of elasticity (MOE) in bending and compressive strength, both parallel and perpendicular to the grain, increase linearly with drying below fiber saturation point (Green and Kretschmann 1994). However, some research indicates that mechanical properties do not always increase with decreasing moisture content. Kretschmann and Green (1996) found that ultimate tensile strength increases as moisture content decreases, reaching its maximum at about 10-12 percent. However, they also note that the ultimate tensile strength then decreases with additional drying below 10 percent.

Exactly what effect does moisture content have on stress wave propagation? The Forest Products Laboratory (1999) noted that the speed of sound propagating through wood decreases with increasing moisture content. It was also noticed that the decrease is proportional to the influence that moisture content has on the modulus of elasticity and density. Halabe and others (1995) observed that wave velocity and bending MOE are significantly higher for dry wood than for green wood. Gerhards (1975) also noted that in solid sweetgum (*Liquidambar styraciflua*), stress wave time increases as the moisture content decreases during five intermediate stages of drying in the range of 150 to 15 percent. Wu (1999) stated that stress wave velocity is affected by approximately 1 percent per 1 percent change in moisture content of the composite panel. Brashaw and others (1997) examined the relationship between moisture content, preservative treatment, and the dynamic MOE. Their results showed a definite relationship between the green and dry dynamic MOE, although they noted that separate regression analysis was required for each species tested.

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Dynamic modulus of elasticity (ED) may be calculated from the stress wave velocity using the following formula:

$$E_D = v^2 \rho$$

Where:
E_D = dynamic modulus of elasticity (Pa)
v = velocity (m/s)
r = density (kg/m^3)

The effect of moisture content on stress wave velocity, and its resultant E_D, has not been adequately addressed. If stress wave velocity is to be used as a tool for performing in situ evaluations of the stiffness for wooden members, then we should consider the effect that moisture content might have on wave velocity. Therefore we initiated this research project to evaluate the extent to which moisture content affected the stress wave velocity in yellow-poplar in a moisture content range of 100 to 10 percent.

MATERIALS AND METHODS

The 100 yellow-poplar (*Liriodendron tulipifera*) specimens used in this study were cut to target dimensions of 0.0508 x 0.0508 x 0.762 meters. Specimens were chosen to be free of any defects, such as sloping grain and knots, and any other form of irregularity that may occur. Specimens were cut from lumber obtained from a sawmill, so it is not certain how many logs were used or how many specimens came from each log. At the start of the study, specimens were at a green moisture content of approximately 100 percent. The specimens were stored in a conditioning chamber in which the temperature and relative humidity were set to provide equilibrium moisture content conditions of 10 percent (22.2 °C and 55 percent relative humidity).

Five stress waves were sent through each specimen over a distance of 0.635 meters and the average wave velocity was used for comparisons. Measurements were performed daily for average dimensions, mass, and stress wave velocity as the specimens air-dried. Once the specimens dried down to approximately 10 percent moisture content, the study was concluded.

At the conclusion of the study the specimens were oven dried to determine the oven dry mass for use in moisture content calculations. Using the measurements, we could track the density, average wave time, and dynamic MOE moisture content dropped.

RESULTS

Ten random samples were taken, without replacement, at each of 10 moisture contents from 100 to 10 percent. The dataset turned out to be not approximately normal, so to meet normality requirements we used the box-cox transformation method. Box-cox transformation is defined as:

$$T(Y)=(Y^l-1)/l$$

Where Y is the response variable and l is the transformation parameter. We then could develop the model:

Wave time X = 38.348126 + 0.3232955MC

Where MC= moisture content in percent.

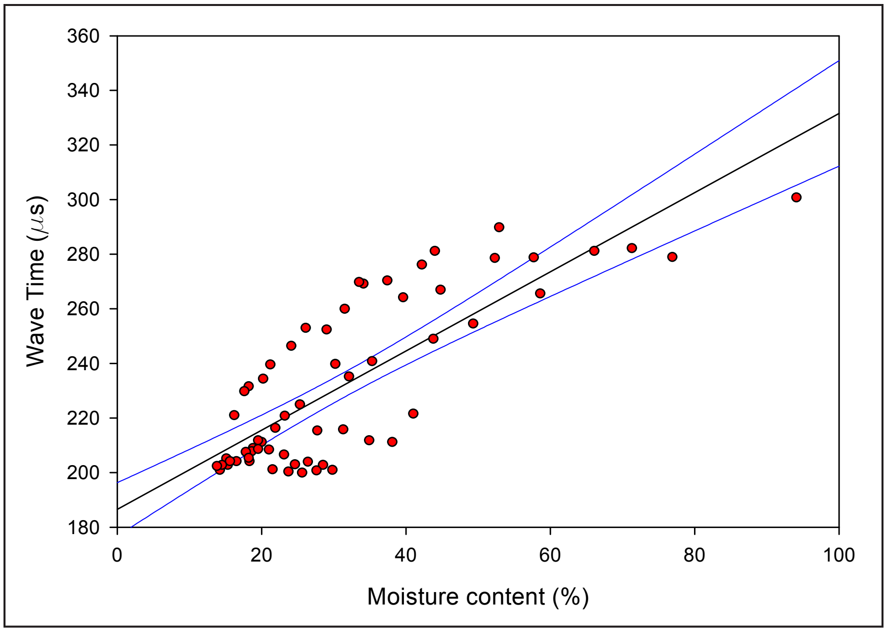

Figure 1.—Regression analysis of moisture content vs. stress wave time r^2 = 0.68, with 95 percent confidence bands.

We derived wave time X through the transformation process using:

$$\text{Wave time X} = (\text{wave time}^2 - 1)/(2*111.1329^2 - 1)$$

Where 111.1329 is the geometric mean.

Figure 1 is a plot of the wave time by moisture content. From this we can see that an approximately linear relationship, r^2 = 0.68, exists between the moisture content of the specimen and its wave time in microseconds.

DISCUSSION

This study indicated that moisture content directly affects the results obtained from the nondestructive testing method being investigated. Moisture content (MC) appears to affect stress wave velocity and the calculated dynamic modulus of elasticity in the same manner that it affects the true modulus of elasticity, determined through static testing. This study was approached from an applied angle to test for an effect of moisture on wave velocity. The model presented in the results section was developed to determine if there was a general relationship present. After 50 percent MC the data appear to be leveling off perhaps because the moisture, rather than the wood, is the dominate influence on wave velocity rather than the wood. Within few data points above the 50 percent moisture content range, the extent of leveling is not conclusive. However, within the typical range of conditions of 10 to 30 percent MC, though, there is a stronger adherence to a linear relationship. Additional data and more extensive investigations on this topic would be required to establish a model that could be used in a predictive manner.

CONCLUSIONS

From this research we conclude that the presence of moisture in wood affects the wave velocity. Therefore, when performing the in situ, nondestructive evaluation described in this research, investigators must take into account the moisture content of the wooden element in question. Failure to do so could contribute to false evaluations.

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DEFECT REDUCTION IN LOW-VALUE WHITE OAK LUMBER USING RESTRAINED DRYING

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Abstract.—Increasing emphasis is being placed on alternative processing methods for low-value hardwoods. Extensive research has shown that drying softwood lumber using edge-wise restraint improves product and value yields. Currently, the effects of restraint drying on product and value yields from low-grade hardwood lumber have not been investigated. We evaluated the use of a modified restraint drying system on its potential to reduce bow, crook, twist, cup, and surface defects in low-grade white oak (*Quercus alba*) lumber. We found that the amount of crook was significantly lower in boards that were dried using pneumatic restraint versus those dried with top-loading only. These results suggest that restraint drying could help secondary processors increase yields and overall returns on low-grade lumber.

INTRODUCTION

In a recent survey of hardwood industry priorities, firms in West Virginia indicated that more research was needed on potential new products and processing technologies that use lower grade logs and lumber (Milauskas and others 2005). Many barriers limit the increased use of this resource. One significant obstacle is the difficulties related to drying low-grade lumber. The presence of high proportions of juvenile and mixtures of flat- and edge-grained wood can increase the tendency of warp during the drying process (Bowyer and others 2003). One of the main components of warpage is crook, which can reduce primary yields (Gatchell 1990). Lumber sawn from small-diameter logs also tends to be shorter in length. The tendency for oak to display crook after drying has been found to be greater for shorter length lumber (Wiedenbeck and others 2003). Furthermore, oak species are more susceptible to drying defects due to their refractory nature and the occurrence of large ray cells (Bowyer and others 2003).

Research has shown that adding weight to the top of a stack of lumber is an effective way to control warp during drying (Denig and others 2000). Top loading can reduce bow and twist, but is less effective at reducing crook (Simpson 1991). Recent research on edgewise restraint drying has shown promise for limiting drying defects in pine lumber (Erickson and Shmulsky 2005, Shmulsky and Butler 2005, Shmulsky and others 2005). Warp reduction was found to be significantly less in boards dried using the restraint system. While these results are promising, the effects of edge-wise restraint on reducing drying defects in hardwood lumber have not been investigated. The objective of this study is to determine the efficacy of using edge-wise restraint to reduce drying defects of low-grade hardwood lumber.

METHODS

Green, low-grade (No. 3 Common) white oak 4/4 lumber was obtained from a local sawmill in West Virginia. At delivery, the majority of this lumber was approximately 6 inches in width and 10 feet long. The lumber was ripped to obtain a uniform width of 5.625 inches. Mostly defect-free 4-foot sections of lumber were then cross-cut from the ripped boards. A total of 140 board sections from approximately 70

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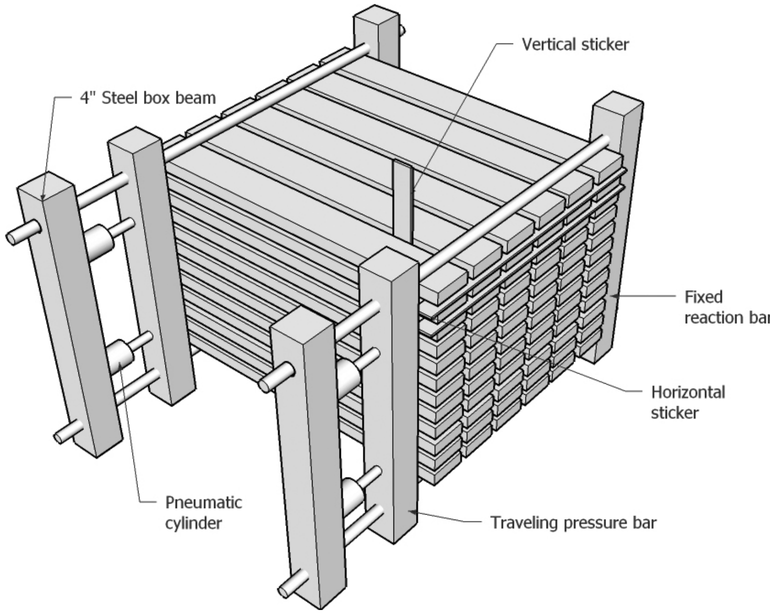

Figure 1.—Three-dimensional schematic of the edgewise restraint device used to assess the impact of restraint on the occurrence of drying defects.

boards were produced for this experiment. All board sections were enumerated and 70 were randomly selected for treatment and the remaining seventy were assigned to the reference group. Before drying, the extent of bow, crook, cup, twist, end-checks, and surface-checks were measured. Departure from the horizontal plane (crook, bow, and twist) was measured on a warp table, using a metal ruler and calibrated wedge. Measurements were recorded to the nearest 1/20 inch. Surface- and end-checks were measured to the nearest 0.125 inch using a metal ruler and/or caliper. The procedure used in this experiment to measure drying defects was modeled after Shmulsky and Butler (2005).

An edgewise restraint system similar to that used by Shmulsky and Butler (2005) was fabricated using a system of metal restraint and traveling bars powered by pneumatic cylinders (Fig 1). Boards were stacked 14 courses high in both the test and control charges. Horizontal stickers were placed on each end of each row, as well as at 12-inch spacings between ends. Because edgewise restraint would have forced the boards together, four sets of vertical ¼-inch x ¾-inch spacers were used uniformly along the length of the stack between each row of boards. The vertical spacers were used to separate the boards edgewise and to promote airflow through the reference and treatment lumber stacks.

Two sets of restraint bars applied a total compressive force of 1,962 pounds to the test charge. Pressure was applied near the end of the boards approximately 3.5 feet apart. This force provided sufficient edge-to-edge pressure to deter tangential movement of the boards during drying. The restraint-system is designed to continue applying equal pressure to the board edges as they shrink in width. The maximum metal-to-wood contact pressure was approximately 18 pounds per square inch. This pressure is far less than the crushing strength of white oak and therefore no damage occurred to the edges of the boards (Green and others 1999). Both charges received approximately 450 pounds (45 pounds/ft^2) of top weight. Sample boards were placed with the kiln charge so that moisture content could be measured (Simpson 1991). The charges were dried in a commercial dehumidification kiln following the moisture content steps recommended for white oak (Simpson 1991). When the average moisture content of the sample boards reached 8 percent, they were allowed to cool to room temperature and the edgewise pressure was released. Following drying and conditioning, we again measured the extent of bow, crook, cup, twist, end-checks, and surfaces-checks on the boards.

Table 1.—Total amount of bow, twist, crook, cup, and number of surface and end checks found in white oak lumber that was dried with and without restraint

	Measured Defect (Inches)	Pre-drying	Post-drying	Difference (Post-Pre)
Reference	Bow	0.15	2.18	2.03
	Twist	3.10	7.83	4.73
	Crook (in^2)	0.00	124.30	124.30
	Cup	0.00	3.03	3.03
	# Surface Checks	10.00	96.00	86.00
	# End Checks	4.00	80.00	76.00
Treatment	Bow	0.33	3.03	2.70
	Twist	2.25	9.13	6.88
	Crook (in^2)	3.72	68.39	64.67
	Cup	0.00	3.77	3.77
	# Surface Checks	3.00	87.00	84.00
	# End Checks	1.00	48.00	47.00

Boards were considered the experimental unit in this study. The following variables were used in the analyses to determine the effect of edgewise restraint on drying defects: bow, twist, crook, cup, average length of surface defects, total length of surface defects, average length of end defects, and total length of end defects. Crook was calculated by determining the triangular area using the maximum length and width of departure from the straight plane. The magnitude of each defect for each board before drying was subtracted from the corresponding measurement of defect after drying to construct the variables for analyses. This allowed us to ascertain the amount of defects due to drying alone. The Shapiro-Wilk test was used to assess the normality of the defect data. Because of the small sample size and the Poisson nature of the defect distributions, the Wilcoxon non-parametric two-sample test of mean dispersion was used in the analysis.

RESULTS AND DISCUSSION

The number and extent of defects was similar in the treatment and reference groups before drying (Table 1). After drying, large increases in the total amount of crook and end checks were noted in the reference group.

Erickson and Shmulsky (2005) and Shmulsky and Butler (2005) found significant reductions in crook, bow, and twist in edge-restrained pine lumber. Following a similar protocol, we found less crook in restrained white oak (0.95 vs. 1.77 square inches; p-value=0.004). Only 22 boards in the restraint dried sample exhibited crook, as compared to 38 boards in the reference group. We found no difference in the amount of twist or bow (Table 2).

Neither Erickson and Shmulsky (2005) nor Shmulsky and others (2005) investigated the effect of edgewise restraint on checking because this is not usually considered a problem when drying pine lumber. However, checking is one of the most common forms of defect in oak lumber. In our study, although not significant, there was weak evidence of an increase in the average total length of end checks in unrestrained versus restrained lumber (p-value=0.102)(Table 2). Further research on the effect of restraint placement on the distribution of surface- and end-checks in oak lumber may be warranted.

Table 2.—Average, with standard deviation in parenthesis, measurement of drying defects in boards dried with and without restraint. P-values generated from Wilcoxon two-sample rank sum test for comparison

Defect	Treatment (restrained)	Reference (unrestrained)	P-value
	----------inches----------		
Bow	0.04 (0.12)	0.03 (0.08)	0.6532
Twist	0.10 (0.14)	0.05 (0.14)	0.3750
Crook (in^2)	0.95 (2.53)	1.77 (2.65)	0.0043
Cup	0.05 (0.05)	0.04 (0.05)	0.2643
Average Length Surface Checks	0.75 (0.87)	0.53 (0.63)	0.1872
Total Length Surf Checks	1.56 (2.37)	1.37 (1.87)	0.5695
Average Length End Checks	0.49 (0.72)	0.66 (0.96)	0.2774
Total Length End Checks	0.89 (1.37)	1.57 (2.82)	0.1018

Drying-induced warp has the potential to significantly decrease yield in hardwood lumber (Gatchell 1990, Wiedenbeck and others 2003). We found that the use of edge-wise restraint during drying of white oak lumber has the potential to decrease the amount of crook, thereby increasing dimensional yields. This is an important finding since the single most important barrier sited among secondary wood processors for the increased use of low-grade lumber is low yield (Pohle and others 2002). Revised techniques for applying edgewise restraint during drying should be investigated since we found some evidence that checking could be reduced using these methods. Likewise, further research should be conducted to see if the use of edge-wise restraint could decrease drying degrade when using accelerated kiln schedules, when drying other species, and when drying higher grade white oak lumber.

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NONTIMBER FOREST PRODUCTS IN DANIEL BOONE NATIONAL FOREST REGION—ECONOMIC SIGNIFICANCE AND POTENTIAL FOR SUSTAINABILITY

Dasharathi Hembram and William L. Hoover[1]

Abastract.—Household members who gather nontimber forest products (NTFP) in and around the Daniel Boone National Forest (DBNF) in eastern Kentucky were interviewed. Participants reported that a wide variety of NTFP were economically and culturally important to them. Forty-three species of plants were sold commercially and 120 were used in households. Ginseng (*Panax quinquefolius* L.) provided the greatest cash income. Social relationships were the primary means of access to private lands. Although the DBNF issues mandatory permits to gather specified products, permit records revealed that no permittee renewed his or her initial permit. This finding casts doubt on the effectiveness of this regulatory approach. Although almost all participants were familiar with the primary ecological and biological characteristics of ginseng, it is not apparent that the institutions necessary for community-based self-regulation required for sustainable harvest levels are present. A regulatory approach, however, is not likely to succeed. The resources necessary for an enforcement program are not available, and it is unlikely that a strict enforcement program would receive the community support necessary for success. We conclude that it would be appropriate to consider the development of community-based programs leading to increased self-enforcement of harvest levels and methods.

INTRODUCTION

The central Appalachian region is one of the poorest rural areas in the nation (Tickamyer and Duncan 1990). It lacks stable employment, opportunities for mobility, diversity of social structure, and investment in community assets (Duncan 1999). In recognition of rural poverty and the potential economic contribution of forest land, policymakers and land managers now emphasize the role of nontimber forest products (NTFP) in forest ecosystem management. The U.S. Congress enacted legislation in 1999 mandating that the U.S. Forest Service (USFS) charge fair market value for NTFP harvesting permits, and ensure that harvesting levels are sustainable. The U.S. Bureau of Land Management, and U.S. Fish and Wildlife Service have also begun to include NTFPs in their plans.

STUDY AREA

This study was conducted in six contiguous counties in the Daniel Boone National Forest (DBNF) region of Kentucky (Hembram 2007). This specific area was chosen because the most recent land management plan of the DBNF emphasizes management of NTFP and communities' socioeconomic needs. Except in one rather urbanized county, more than 85 percent of the population lives in rural, isolated, hilly areas with an average population density of 46.7 persons per square mile. Communities are characterized by geographical isolation, and persistent and chronic poverty. They are economically distressed as measured by poverty, unemployment, and per capita income (Appalachian Regional Commission 2006).

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Two primary models have been advanced for the causes and possible remedies for Appalachian poverty. The "culture of poverty" model explains poverty in terms of the behavior of families and individuals, and the social dynamics interconnected to geographical, socio-cultural, and economic isolation. The model links poverty to the mountain culture and value systems embedded in individualism, traditionalism, and fatalism. It also suggests that cultural and geographical isolation has led residents to resist programs that would bring them into contact with the outside world, thereby improving their economic lives (Weller 1965). The "internal colonialism" model views Appalachian residents and the region's natural resources as having been exploited by absentee corporate owners who monopolized land, mineral resources, and politics in the region. Caudill (1962) in his classic work on cultural and economic history of Appalachian Kentucky advanced the internal colonialism model by linking it to the cultural isolation of mountaineers.

Nontimber Forest Products

The concept of NTFP is ambiguous (Belcher 2003), but generally refers to all biological materials other than timber extracted for human use from within and on the edges of natural, manipulated, or disturbed forests. According to the United Nations, Food and Agricultural Organization, NFTP consist of goods of biological origin other than wood, derived from forests, other wooded land and trees outside forests (Vantomme 2003). These products are derived from plants, fungi, ferns, mosses, animals, and their parts. People use them as food, medicine, decorations and ornaments, furniture, crafts, and utensils to be consumed at home or exchanged in markets for cash income. In both developing and developed countries, collection of these products generally falls outside the formal market economy.

Informal Economic Activity

The term "informal economic activities" refers to activities that lie outside the scope of the institutional regulations of the state and social environments where similar activities are regulated (Portes and Haller 2005, Portes and Sassen-koob 1987). These activities may be inherently illegal or simply escape taxation and inclusion in the economic data used to determine qualification for social services and welfare. Many scholars include in this category both non-monetized activities and market exchanges such as barter, self-provisioning of goods and services, and domestic works used as livelihood strategies (Jensen and others 1995, Mingione 1991, Tickamayer and Wood 1998).

Access

Access refers to social actors' ability to use a resource given all the rights and opportunities they face. Access to natural resources is mediated through institutions defined by statutes and regulations, social norms, norms of behavior, and conventions that prohibit and/or permit individuals to undertake activities within their social settings (Leach and others 1999, Ribot and Peluso 2003, Mehta and others 1999, North 1990, Scoones 1999). Formal institutions that legitimize effective control and command over natural resources are property rights (Bromley 1992, Schlager and Ostrom 1992). Social scientists recognize a parallel mechanism of access, one where social actors gain access to resources through social connections, i.e., social capital (Coleman 1990, Lin 2001).

Based on property rights, resources can be private property, common property, state property, or open access depending on who has rights to derive benefit streams from a resource and regulate access by other users. Open-access resources are free of entry costs for all users since no mechanism is in place to regulate access. In other instances, exclusion of potential users is difficult by any means due to the nature and extent of the resource (Berkes and others 1989, Ostrom and others 1999). Such resources become de facto open access.

In Kentucky, about 89 percent of forest land is privately owned (Smith and others 2004). Within the DBNF proclamation boundary, nearly 67 percent of forest land is private and 33 percent is owned by the U.S. Forest Service and state agencies. Access to the DBNF is regulated by a permit system depending on the product and use. The harvesting permit for personal consumption of permitted NTFP is free, but the Forest Service charged a fee of $20 for each permit used for commercial harvesting. Collection of ginseng root required payment of fees regardless of commercial or personal use. This permit had both enabling and constraining features. It enabled holders to enter onto DBNF lands and withdraw a specified category of products, but the gathering was constrained by restrictions on time, duration, season, location, and harvest level. The permit holders for ginseng roots were required to dig only plants at least 10 years of age, plant back one-half of the seeds from the harvested plants within 50 feet of the harvest site, and bring the other half of the seeds to the office of the Ranger District issuing the permit. There is no enforcement mechanism for these regulations.

American Ginseng

American ginseng is one of the most commercially important NTFP in North America. Total export of wild harvested dry ginseng root in the United States in 2001 was 150,000 pounds worth U.S. $59 million (Chamberlain 2005). It is a perennial forest herb ranging from Quebec and Manitoba in Canada to northern Florida, Alabama, Louisiana, Arkansas, and Oklahoma in the United States (Anderson and others 1993). Its tuberous roots are dug primarily for export as a herbal medicine. Large-scale domestic cultivation takes place in the United States; however, wild roots command higher prices than cultivated roots. The wild population is declining and becoming rare throughout its North American range (U.S. Fish and Wildlife Service 2005). In 1973, the species was listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Flora and Fauna, enabling regulation of its trade (Robbins 1999).

Sustainable Harvesting Practices

We examined harvesting practices for American ginseng. Analysts of traditional ecological knowledge (TEK) suggest that resource users with historical continuity in resource use are more likely to carry out sustainable practices through appropriate institutions and social norms. Such societies are generally non-industrial or less technologically advanced, many of them indigenous or tribal (Berkes and others 2000). Since we were studying a population in a developed country, we carefully investigated the prevalence of these practices through in-depth interviews. The objective was to determine whether historical continuity in the use of NTFP existed in the households included in our interviews.

METHODOLOGY

We used a mix of qualitative, inductive inquiry and quantitative measurements similar to Patton (1990). Identifying and gaining access to harvesters was problematic because these activities are of dubious legality (Gaughan and Ferman 1987). An initial sample of harvesters was identified from the permit records of the DBNF. The sample was expanded by snowball and respondent-driven sampling, and through referrals. Twenty-five participants from 21 households were eventually recruited. In-depth interviews were conducted by the lead author using a set of semi-structured open-ended questions. Interviews were tape recorded when participants consented; otherwise responses were journaled. Transcripts and journals were analyzed following Strauss and Corbin (1998). Open coding was used to capture these concepts and ideas and to link and organize them into initial categories. The frequently recurring codes were compared in an effort to understand the issue and develop categories. Selective coding was used to further develop and refine categories.

RESULTS

The nature of the subject and sample population make it very difficult to draw definitive conclusions. The sample size was not adequate to represent the entire population of NTFP gatherers in the DBNF region. In addition, there was no way to verify the estimates of quantities provided by respondents. Nevertheless, the results shed light on the sustainability of critical NTFP given the existing institutional arrangements and harvesting practices.

Economic Significance

Participants were diverse in terms of gender, age, ethnicity, educational attainment, and household attributes. Seventy-five percent had an educational level of high school or less. Three were employed at the time they were interviewed. Annual household income of nearly half of the households was less than $10,000, below the poverty threshold for 2005.

They reported use of organs and tissues from 105 forest species, including bark, twigs, branches, sap, roots, wood, flowers, leaves, shoots, vines, fruit, nuts, berries, ferns, mosses, and mushrooms. These products were used for food and beverages, medicine, decorative materials, firewood, crafts and furniture, and oils, dyes, and perfumes.

A majority of these products were consumed by the harvesters or members of their households. Edibles and medicinals constituted the bulk of the products for home use. The 46 wild edibles reported included mushroom, berries, nuts, fruits, wild greens and ferns. Although not the primary source of food, they supplemented diets and saved money by replacing purchased food. Although some participants quantified their annual consumption, the quantities reported are not reliable because of cognitive limitations, and over- and understatement by participants to please outside researchers. Nevertheless, their responses clearly indicate the importance of NTFP to their household budgets.

In aggregate, respondents reported using 49 plant species for herbal medicine at home. Their use was described as a “mountain” or cultural tradition. Participants attributed their use to a number of factors, including family tradition derived from TEK and practices, household income, and actual efficacy of herbal medicine or socially embedded beliefs about their usefulness. However, 20 percent of households indicated that use of NTFP started with their generation, motivated by their need for additional income and their ability to learn about harvesting practices from other members of their communities.

A large number of marketed products contributed significantly to annual household income. Cash income came primarily from roots and bark of medicinal plants, including ginseng, goldenseal, blood root, black cohosh, blue cohosh, trillium, lady’s slipper, wild ginger, Virginia snake root, star grove, cranesbills, Indian tobacco, sassafras, mullein, wild yam, spikenard, stone root, willow, slippery elm, walnut, sumac, catnip, boneset, and papaw. Other tradable products included moss, decorative plant materials such as grapevine and Christmas tree, and wood-craft products. Certain wild edible products were also traded locally. Among the tradable medicinal products, ginseng root commanded the highest price in the local market, about $350 a dry-pound. The price of other materials ranged from less than a dollar to nearly $60 a dry-pound. Harvesters reported that they focused on those products with the highest net payoff when the market price is compared to the total cost to gather and market.

We attempted to quantify the proportion of households that relied on NTFP for income and their contribution to total annual household income. We asked participants to recall the annual quantity of each of the products they sold and the income received. We assume that participants tended to underreport income to avoid tax or the denial of welfare benefits (Gaughan and Ferman 1987). A local buyer reported that many harvesters in the region have a "fixed, stable income" in the form of government welfare benefits and for this reason, they did not want to be identified or they did not want to reveal income information.

Household income from selling NTFP depended on time spent on harvesting activities. Household members who harvested full time during the season earned more money than those who harvested less frequently. Responses indicate that full-time harvesters earned about $3,000 annually. Other households reported NTFP income of $200 to $1,000 annually. According to local buyers, a few harvesters earned as much as $5,000 to $15,000 annually.

Access Mechanisms

Participants relied more on private forest lands than on the DBNF due to its limited geographical area and permit requirements. They also objected to the process used to issue permits, notably the need to interact with USFS employees.

An analysis of permit records revealed that participants drawn from the pool of permit holders did not purchase harvesting permits every year, but most continued to harvest commercially on a regular basis. In addition, based on the volume purchased by buyers, the number of harvesters in the region was estimated to be higher than the number of permits issued: 11, 6, 15, 63 and 45, respectively, for 2000 through 2004. Each of the local buyers interviewed reported purchasing from as many as 100 individuals in the region every year.

Access to private forest lands was mediated through social relationships. Harvesters required permission from the landowners who provide discretionary access. Permission was oral and free of cost. The harversters' ability to get permission from a landowner depended on their social relationships, which ranged from mutual acquaintance to strong personal ties. Responses suggest that when a personal acquaintance is lacking, access was denied, indicating the discretionary nature of access.

We have not investigated why private landowners provided access to other individuals to derive economic benefits from their lands. The participants' accounts, however, provide important insights. According to them, the majority of landowners granting them access did not make use of these resources themselves. However, with the growing awareness and market opportunities, more landowners have begun to derive NTFP benefits for themselves. As a result, access to such lands is getting stricter. In addition, participants' accounts and indirect evidence suggest that harvesters in the region resort to illegal access on both the DBNF and private forest lands.

Harvesting Practices

Nearly 90 percent of participants stated that they have harvested ginseng. It is the most important NFTP for these households because it commands the highest unit price in the local market.

Harvesting practices narrated by participants included temporal restrictions, protection of young plants, area rotation, artificial regeneration and retention of mature plants, and monitoring of resource abundance. According to Berkes and others (2000), these are the practices for adaptive management of ecosystems and biological diversity to secure a sustainable flow of natural resources and ecological services. However, interviewees gave no indication of any social institutions for self-governance within the community of harvesters.

DISCUSSION AND CONCLUSIONS

NTFP in the central Appalachian region play a significant role in the economic lives of poor rural households. They fit into the diversified livelihood strategies adopted by rural households. The consumption of edible, medicinal, and other NTFP supplements diets, medicinal and other livelihood needs, and reduces costs. Individuals who pursue harvesting full time for cash income can earn $3000 or more per year. These harvesters are also at the bottom of the socioeconomic strata with annual household income of less than $10,000. Even if the monetary value of materials used in home consumption is not included, more than 30 percent of total household income may come from forests. Estimates of income are very rough because of cognitive problems associated with recall, small sample size, and people's reluctance to reveal their actual income. However, this study gives clear indications that these products are an important source of income that should be studied further.

Most forest land in the DBNF region is in private hands. Our findings suggest that household members in the study region rely more on privately owned forests than on the DBNF, indicating the importance of access to private forests as an income source for non-owners of forest land.

Harvesters adopt multiple access mechanisms. They recognize the social relationships of private property rights. They ask landowners for permission to harvest. Although access is free, it is not a generalized social norm. Rather, landowners provide discretionary access to individuals with whom they have social ties. Many private landowners pay limited attention to "minor forest products" on their lands and thus may believe they are not giving up too much. With growing awareness of the high market values for plants, such as ginseng and goldenseal, they have begun to look for ways to capture for themselves, the benefits that largely go to others. This new relationship can have direct influence on access mechanisms and the present role of private lands in providing benefits to poor non-owners.

Access mechanisms observed in the study region are considerably different from those of rural households in tropical countries. In these countries, poor unskilled household members who lack access to labor markets harvest the products for food and income as a gap-filling mechanism or as a means to survive unprecedented emergency situations. They use products harvested from forests as de jure or de facto open-access resources (Angelson and Wunder 2003).

This study demonstrates that knowledge of appropriate resource use practices exists among resource users in developed as well as non-indigenous societies, where users may not have legitimate command and control over the resource through appropriate institutions and social norms. The pervasiveness of these practices across central Appalachia, however, requires further empirical investigation.

There are a number of self-enforced resource use practices among harvesters that are necessary but not sufficient for sustainability of economically important NTFP. The institutions necessary for community self-governance to regulate sustainable harvest levels, however, are not present, making it appropriate to consider the development of community-based programs leading to increased self-enforcement of harvest levels, stakeholders' participation in resource management, and sustained livelihoods. However, the lack of such institutions, despite numerous attempts by government agencies and faith-based organizations to organize them, is a root cause of poverty in the region. Thus, resource managers are faced with a challenge outside the bounds of their normal sphere of influence.

We suggest that economic policies to improve rural livelihoods in the Appalachian region must continue to take these resources into consideration. However, policies should focus on social and economic processes that are likely to improve the overall long-run economic welfare of people in the region, rather than a regulatory approach based on enforcement activities. The resources necessary for an enforcement program are not available, and it is unlikely that a strict enforcement program would receive the community support necessary. As participants' accounts and vast literature indicate, household members continue to engage in extraction activity due to lack of employment and alternative livelihood opportunities. When better livelihood opportunities are available, reliance on these resources should decline.

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U.S. HARDWOOD LUMBER PRODUCTION: 1963 TO 2003

William Luppold and Matthew Bumgardner[1]

Abstract.—Between 1963 and 2003 northern hardwood lumber production more than doubled while production in the southern regions increased by less than 25 percent. In 1963 the major users of hardwood lumber were the furniture manufacturers located in the southeast region, and hardwood flooring producers located in the south central region. By contrast more than 60 percent of the kitchen cabinet and pallet industries were located in the northern region. Decreased production of flooring, increased concentration of the furniture industry in the southeast region, and increased production of pallets resulted in production plummeting in the south central region, while increasing in the northeast, north central, and southeast regions. Between 1982 and 2002 lumber consumption by the furniture industry had declined as imported furniture caused the domestic industry to contract. By contrast, production of kitchen cabinets, flooring, pallets, and exports surged, causing production in the northeast, north central, and south central regions to increase. As a result of shifting domestic and international demand and an adequate sawtimber resource, southern and northern production became nearly equal by 1992 and has remained relatively equal since then.

INTRODUCTION

Between 1963 and 1999 eastern hardwood lumber production increased by 73 percent, or more than 5 billion board feet (Fig. 1). Beginning in 1999, the hardwood lumber industry suffered through 4 years of declining production before experiencing small increases in 2004 and 2005. While decreases in eastern hardwood lumber production between 1999 and 2003 were similar across regions, most of the increases in production prior to 1999 were in the northeast and north central regions (Fig. 2, Table 1).

It is important to understand shifts in hardwood lumber production because sawlog harvesting is a major source of timber removal and forest disturbance. Therefore, understanding how changes in hardwood lumber use and sawtimber availability have influenced hardwood lumber production is crucial in assessing

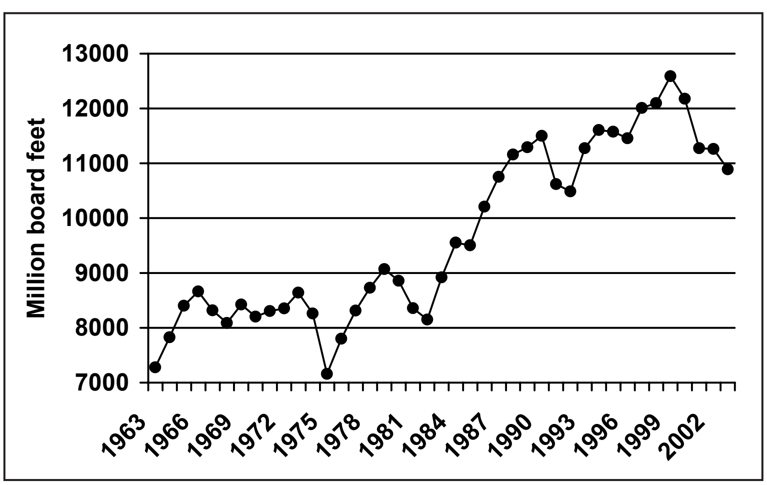

Figure 1.—Estimated eastern hardwood lumber production 1963 to 2003.

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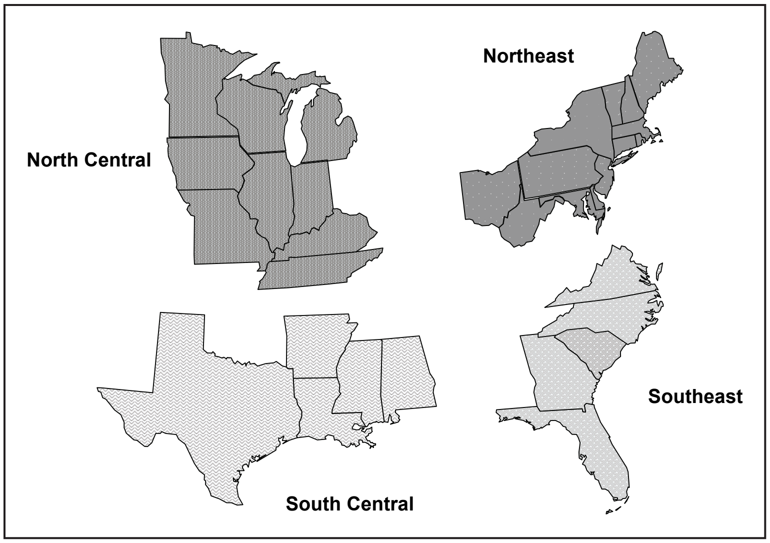

Figure 2.—Delineation of eastern forest survey regions.

Table 1.–Regional lumber production in million board feet (MMbf) and percentage basis for peak production years in the eastern United States

	Northeast		North central		Southeast		South central		Total
Year	(MMbf)	(%)	(MMbf)	(%)	(MMbf)	(%)	(MMbf)	(%)	(MMbf)
1963	1,509	21	1,225	17	1,585	22	2,958	41	7,277
1972	2,073	25	1,530	18	1,832	22	2,921	35	8,356
1982	2,304	28	1,582	19	1,963	24	2,302	28	8,151
1992	3,013	29	2,346	22	1,889	18	3,240	31	10,488
1999	3,672	29	2,817	22	2,295	18	3,804	30	12,588
2003	3,112	29	2,424	22	1,992	18	3,361	30	10,889

the impacts of markets on forests. Other studies linking lumber production to sawtimber availability and demand have been conducted at the state level (Luppold and Bumgardner 2006).

METHODS

In this paper, we examine regional (Fig. 2) hardwood lumber production from 1963 to 2005 and link these changes in production to regional species composition and lumber demand. The biggest factors that affect hardwood lumber production, at least in the short run, are where specific industry sectors have chosen to locate and what species are currently fashionable in both domestic and international markets. Regional analysis is critical to understanding the influence of sector-level demands (e.g., furniture, flooring), which tend to be concentrated regionally, on hardwood lumber production.

Since the early 1960s, the hardwood lumber market has been dynamic with respect to production and consumption. The continual change in the market makes it difficult to identify at what points to examine these changes. For this paper we have chosen six periods: 1963 to 1972, 1972 to 1982, 1982 to 1992, 1992 to 1999, 1999 to 2003, and 2003 forward. The first period was defined by the availability of data (Census of Manufacturing), the second and third periods were selected because they began and ended with economic recessions, and the 1992 to 1999 period was selected because production rose to an all-time high in 1999. Similarly, the 1999 to 2003 period was selected because of the 4 continual years of declining production. Since 2003 we have seen market realignment, but it is still too early to confirm if these trends will continue.

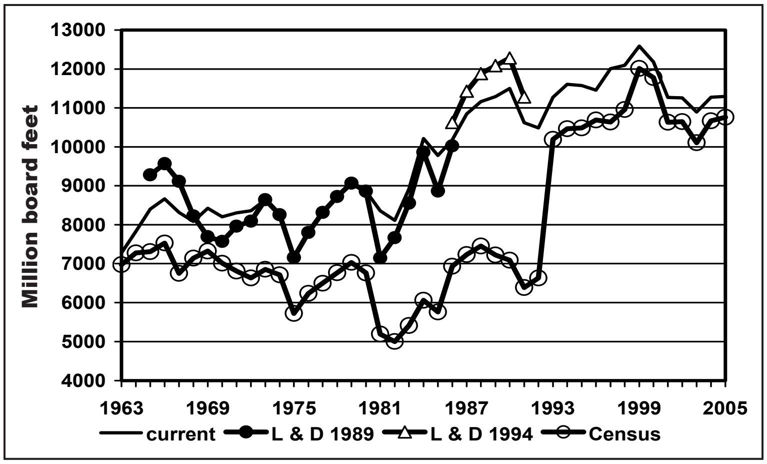

Figure 3.—Comparison of current estimates of hardwood lumber production with those of Luppold and Dempsey (1989, 1994) and USDC Census revised estimates 1963 to 2005.

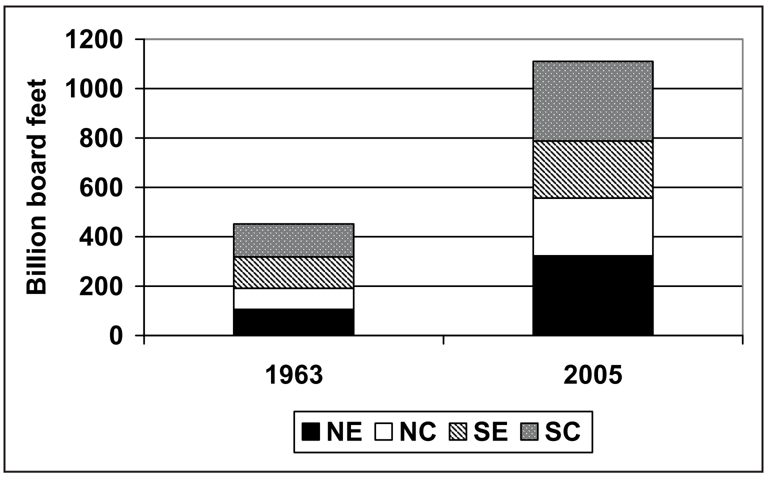

Figure 4.—Eastern hardwood sawtimber inventory in 1963 and 2005.

Data Considerations

Between 1960 and 1994 the U.S. Department Commerce (USDC) Bureau of the Census underestimated hardwood lumber production (Fig. 3). Identification of this problem led to the development of alternative estimates (Luppold and Dempsey 1989, 1994). For this analysis, the incorporation of additional information supplied by the U.S. Forest Service and state forestry agencies and redefinitions of regions required new estimates based on the procedures described in Luppold and Dempsey (1989, 1994).

Changes in Sawtimber Inventory

Hardwood lumber production is inherently linked to sawtimber inventory. In 1963 the eastern regions of the United States contained more than 450 billion board feet (bbf) of hardwood sawtimber (Fig. 4). However, the southern regions contained 58 percent of the eastern sawtimber resource. By 2005 inventories of eastern hardwood sawtimber exceeded 1.2 trillion board feet with 56 percent of this increase occurring in the northern regions (Table 1). This shift in inventory resulted in near parity between the northern and southern hardwood sawtimber inventories in 2005 (Fig. 4).

It should be noted that much of the increase in inventory over the last 40 years was a result of the transition of small-diameter growing stock into sawtimber-size material (termed in-growth). These trees regenerated during three distinct periods. Many of the red oak species regenerated after a virtual clear cut of both

Table 2.—Hardwood lumber consumption in the United States by major industries for selective Census years

Industry	1963	1972	1982	1992	1997	2002
	-----------------------------------Million board feet-----------------------------------					
Wood furniture	1,594	1,926	1,613	1,546	1,592	1,248
Upholstered furniture	671	865	545	663	492	442
Office furniture	173	213	322	484	573	371
Kitchen cabinets	221	293	312	898	1,266	1,367
Millwork	256	614	436	644	726	923
Other building products	48	212	307	342	539	684
Pallets and containers	1,201	1,486	2,508	3,127	4,109	3,666
Crossties	500	850	834	578	884	928
Flooring	1,622	706	386	755	1,162	1,191
Miscellaneous	492	1251	873	956	740	567
Total domestic	6,778	8,416	8,136	9,993	12,083	11,388
Exports	131	237	321	919	1,213	1,162
Total domestic plus exports	6,909	8,653	8,457	10,912	13,296	12,550

hardwood and softwood forests between the late 19th century and the early 20th century and associated widespread slash fires. As marginal farmland was abandoned during and after the Great Depression, shade intolerant/pioneer species (e.g., yellow-poplar) regenerated on these lands (Clarkson 1964, Carvell 1986). After World War II, shade-tolerant species such as red and sugar maple started to regenerate, apparently because increased selective harvesting patterns resulting in incomplete canopy removal.

States in the northern regions contain significant quantities of softwood timber, but more than three-quarters of the sawtimber inventory are hardwood species (USDA Forest Service 2006). The northeast region contains relatively large quantities of soft maple (primarily red), select red oak (mainly northern red oak), and hard maple. The north central region also contains relatively high quantities of select white oak, other red oak (primarily black oak), select red oak, and hard maple. The apparent increase in proportional sawtimber volume in the south central regions is largely the result of increased sawtimber inventories in Kentucky and Tennessee. By 2005 nearly 40 percent of the south central sawtimber inventory was within these states.

The composition of forest in the southern regions is evenly distributed between hardwoods and softwood species (USDA Forest Service 2006). The predominant hardwood species in the southeast region include yellow-poplar, sweet and black gums, other red oaks (including laurel, southern water, scarlet, and black oak) and select white oaks. Other red oaks (including water, southern red, black, and scarlet oak), gums, other white oak (including chestnut, post, and overcup oak), and select white oak are the predominant species.

RESULTS

1963 to 1972

In 1963 more than 40 percent of hardwood lumber was produced in the south central region (Table 1) even though this region contained only 30 percent of the hardwood sawtimber (Fig. 4). This apparent imbalance was the result of the large market for flooring (Table 2) and the high concentration of flooring and dimension manufacturers in this region as measured by regional proportion of total value of shipments

Table 3.—Changes in regional relative value of shipments for major hardwood lumber consuming using industries 1963, 1982, 2002 in the United States

Industry	Year	Northeast	North central	Southeast	South central
		---percent---			
Wood household furniture	1963[1]	21	19	44	16
	1982[2]	18	13	54	15
	2002[3]	26	19	42	13
Flooring	1963	3	12	18	67
	1982	NA	NA	NA	NA
	2002	NA	NA	NA	NA
Dimension	1963	23	17	18	42
	1982	24	16	21	39
	2002	NA	NA	NA	NA
Kitchen cabinets	1963	40	31	17	12
	1982	31	29	19	21
	2002[4]	30	38	17	16
Pallets	1963	38	29	14	19
	1982	29	31	17	23
	2002[5]	24	31	20	25

[1] USDC Bureau of the Census 1966
[2] USDC Bureau of the Census 1985
[3] USDC Census Bureau 2004a
[4] USDC Census Bureau 2004b
[5] USDC Census Bureau 2005

(Table 3). In 1963 the northeast region produced nearly as much lumber as the southeast but contained a lower volume of hardwood sawtimber. The north central region produced only 17 percent of eastern lumber in 1963, which seems to be consistent with the relatively low level of sawtimber inventory.

Between 1963 and 1972 hardwood lumber production increased by more than 15 percent as lumber use increased for nearly every lumber-consuming industry other than flooring. While production in the south central region decreased by 1 percent, production in the northeast, north central, and southeast regions increased 37, 25, and 16 percent, respectively. The decrease in lumber production in the south central region and a relatively small increase in the southeast region were largely the result of reduced flooring production. As flooring production dropped by more than 50 percent, south central flooring plants shifted to dimension production as nearly all the increase in lumber consumption during this period was in the form of dimension purchases (USDC Bureau of the Census 1966, 1976). Because of these shifts, combined northern production increased from 38 percent to 43 percent of total eastern production.

1972 to 1982

During this 11-year period hardwood markets experienced variations in price and production as the U.S. economy endured two recessions. Demand changed significantly as furniture fashion shifted from closed grained species (maple) to open grained species (oak), and pallet production increased (Table 2). These changes caused major shifts in hardwood lumber production from the south to the northeast.

The most significant shifts were the 600-mmbf decline in the south central region as hardwood flooring production hit a post-World War II low. The increased preference for red oak in furniture, a growing export market, and increased pallet demand caused production in the northeast to increase by 250 mmbf.

Even though furniture production declined between 1972 and 1982 (Table 2), the furniture and dimension industries became more concentrated in the southeast region (Table 3). While production in the north central region increased with increased export and pallet demand, the decline in hard maple prices during this period seemed to have a disproportionate influence on hardwood lumber production in the Lake States. As a result of these changes, the northern region accounted for more than 47 percent of eastern hardwood lumber production in 1982.

It should be noted that hardwood production declines during periods of recession because of not only reduced production of secondary products, but also the tendency of secondary manufactures to reduce lumber inventory. This drawdown in inventory also explains the surge in price and production after these periods as secondary processors increase lumber consumption and inventories simultaneously.

1982 to 1992

After 1982 hardwood lumber production surged to 11.5 bbf in 1990 before declining in 1991 and 1992. Still, the mid-1980s was the first time that hardwood lumber production exceeded 10 bbf since 1913. However, this increase in production was inconsistent across regions. Between the 1982 and 1992 recessions, hardwood lumber production in the north central and northeast regions increased by nearly 50 and 30 percent, respectively. This increase was influenced by increased production by pallet and kitchen cabinet firms that were more heavily concentrated in these regions (Table 3), increased exports, and an increase in demand for hard maple.

Between 1982 and 1992 hardwood lumber production increased 40 percent in the south central region as a result of increased flooring production and an expansion of the pallet and kitchen cabinet industries. By contrast, hardwood lumber production declined in the southeast as demand by the furniture industry remained flat. The decline in hardwood lumber consumption by the furniture industry also was related to the increased volume of furniture imports during the 1990s. By 1999, hardwood lumber production in the combined northern and southern regions would be virtually equal.

1992 to 1999

Between 1992 and 1999 production increased in all regions at similar rates as consumption by all industries increased. Even the furniture industry increased production although imports continued to climb. The most significant change during this period was the continual increase in industrial product consumption and consumption by construction-related industries, including kitchen cabinets, millwork, flooring, and other building products. While lumber consumption by these industries had been steadily growing since 1982, it reached parity with combined consumption by the furniture industries only in 1992 (Table 3). Between 1992 and 1999 hardwood lumber consumption by the furniture industries increased slightly, but lumber use by construction and remodeling manufacturers surged.

1999 to 2003

After reaching an all-time high in hardwood lumber production in 1999, the hardwood lumber industry declined by 1.7 bbf over 4 years (Fig. 1). This was the first time that hardwood consumption had declined for 4 consecutive years in the recorded history of annual hardwood lumber production starting in 1904 (Steer 1948). Although most of this decrease was the result of a decline in consumption, the liquidation of inventories at furniture plants also contributed. While furniture production decreased in all regions, the southeast had the greatest relative decline in terms of value of shipments due to the high proportion of furniture manufacturing located there (USDC Census Bureau 2004a).

The unusual aspect of this period was that as the pallet and furniture industries' consumption of hardwood lumber declined, consumption by manufacturers of construction and remodeling products increased. By 2002, combined consumption by construction and remodeling industries was twice the combined consumption by the furniture industry. Hardwood lumber consumption by the pallet industry declined as pallet and pallet part recycling increased. This recycling effort was in part triggered by increased prices of low-grade oak lumber resulting from continual use of these species by the flooring industry. Export demand also was changing during this period as China became an important market for U.S. hardwoods. These shifts in markets resulted in a uniform decline in lumber production across all regions.

Another example of markets expanding in this period was the Amish furniture manufacturing clusters located in portions of Ohio, Pennsylvania, and Indiana. These clusters are characterized by high concentrations of small firms collectively generating significant regional lumber use.

DISCUSSION

This analysis demonstrates that regional shifts in hardwood lumber production result from an interaction of changing demands for hardwood lumber, location of lumber-using industries, and attributes of the sawtimber inventory. Many of the changes in demand over the past 40 years would have been difficult to project. However, there are several known aspects about the hardwood resource and market that can provide insight on how production may change in the future.

One factor that influences long-term regional production trends is sawtimber supply because secondary industries seeking to expand production want to locate close to supplies. Species diversity also may influence regional production because style trends cycle and different species move in and out of vogue. Therefore, states or regions that have relative high volumes of timber and a broad composition of species may experience more consistent harvests of hardwood sawtimber.

For years the demand for higher grades of hardwood lumber came from large furniture, wood flooring, and kitchen cabinet manufacturers. Today much of the commodity products portion of these industries is facing international competition. By contrast, a driver of growth in hardwood lumber demand seems to be smaller manufacturers producing custom and semi-custom products; these manufactures are difficult to track. As time progresses, it may become increasingly difficult to examine how demand influences supply, particularly at regional levels, without developing more information on the smaller consumers of hardwood lumber.

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SYNTHETIC ROPE APPLICATIONS IN APPALACHIAN LOGGING

Ben D. Spong and Jingxin Wang[1]

Abstract.—New ultra-high molecular weight polyethylene rope has shown good results as a replacement for wire rope in logging applications in the western United States. A single case study trial was performed in Appalachian forest conditions to assess the appropriateness of this technology for hardwood logging applications. The study focused on use of the rope in West Virginia and included a review of the legal status for using synthetic rope in logging and informal interviews with loggers and forest managers to understand which applications might be appropriate and what specifications are required for length, strength, and other characteristics. A 125-foot length of 5/8-inch synthetic rope was purchased and installed on a bulldozer for this case study. The synthetic rope has a premium price almost double that of wire rope. Such potential benefits as improved worker conditions, greater productivity, and decreased negative environmental impacts may lead to wide adoption and eventually lower prices. Trials were observed in a logging operation and road-clearing operation in which the rope performed well and loggers were impressed by the strength, ease of splicing, light weight, and flexibility of the rope. The trial illustrated issues, concerns, and possible techniques that may be applied by others seeking to be early adopters of this technology.

INTRODUCTION

Appalachian hardwood timber harvesting activities rely heavily on ground-based equipment for log extraction. A typical cable skidder or bulldozer is often used with a wire rope cable attached to a drum winch at the back of the machine. This winch line is used to pull logs in from the stump location to the machine, which is positioned on a skid trail. Once the logs have been pulled into the skid trail, they are pulled down the skid trail to a roadside landing. Wire rope has been used in these types of operations since the turn of the last century with slight improvements to increase strength, longevity, and other operational characteristics of the wire rope. While many of wire rope's characteristics are well suited for logging, other characteristics make working with wire rope difficult and at times dangerous. Wire rope is primarily constructed from steel, which although strong, is very heavy, will deform under stress and bending, stores energy under load, and can have very sharp edges and ends.

Ultra-high molecular weight polyethylene (UHMWPE) ropes can be substituted for wire rope in many logging applications to decrease many of the less desirable qualities of wire rope (Fig. 1). With increased flexibility and the weight per foot equivalent to one-ninth the weight of steel rope of similar diameter and strength (Pilkerton and others 2003), the rope is much easier to work with (Garland and others 2002). The reduced effort required by the logger means longer winching distances and increased abilities to work in and around sensitive areas are possible (Ewing 2003, Golsse 1996). Additionally, trials using UHMWPE have demonstrated some improvements in productivity with time savings of approximately 10 percent over use of wire rope (Garland and others 2002) because the synthetic rope is easy to carry, spool, and splice.

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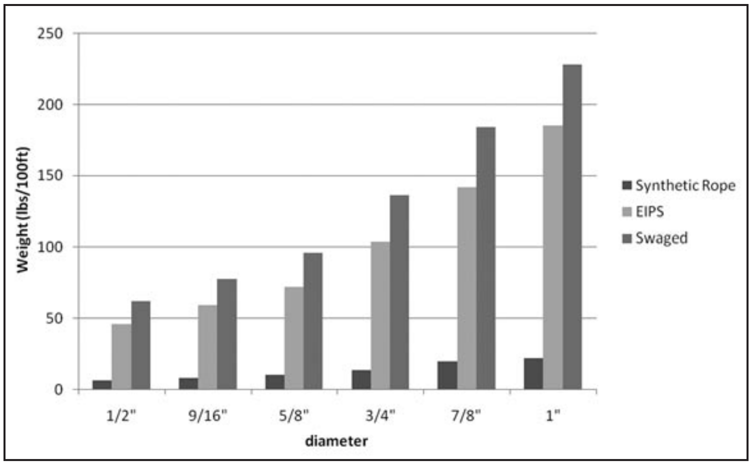

Figure 1.—Weight per foot of logging wire rope and UHMWPE synthetic rope at commonly used diameters.

In light of the many favorable applications and characteristics identified and tested in the West, a case study trial was established in Appalachian forest conditions to assess the appropriateness of this technology for hardwood logging applications.

METHODS

A case study investigation was utilized to address the feasibility of synthetic rope in Appalachian logging conditions and identify additional variables and questions for further research. The use of synthetic rope is an emerging topic in forest harvesting research, there is little experience with this topic in general, and even less with direct applications in Appalachia. To address these needs, the case study research methodology begins with preliminary data collection from the following sources:

1. State and Federal agencies and published legal references
2. Synthetic rope manufacturers and distributors
3. Logging machine equipment distributors and published reference materials
4. Informal interviews with logging contractors regarding experiences and needs.

Given the favorable feedback from the preliminary data, the researchers purchased 125 feet of 5/8-inch diameter synthetic rope and installed the rope on a skidding dozer as a field trial. Follow-up data were collected from the machine operators after the initial installation and after using the rope for 1 day, 1 week, and finally after 1 month.

RESULTS

A review of federal Occupational Safety and Health Administration (OHSA), West Virginia state, and other regulations that apply to West Virginia indicates that no regulations explicitly require the use of any particular material for the cable or rope used in winching or other logging activities. Some other states with additional local OSHA standards specify the type and sometimes size of wire rope to be used in certain logging applications, such as in the state of Alaska (2003).

Given the legal ability to use synthetic rope for logging operations in West Virginia, logging applications were identified for use in the case study. The obvious application was the replacement of wire rope on the back of a cable skidder or dozer used to drag logs to the landing. Log skidding is the primary activity where

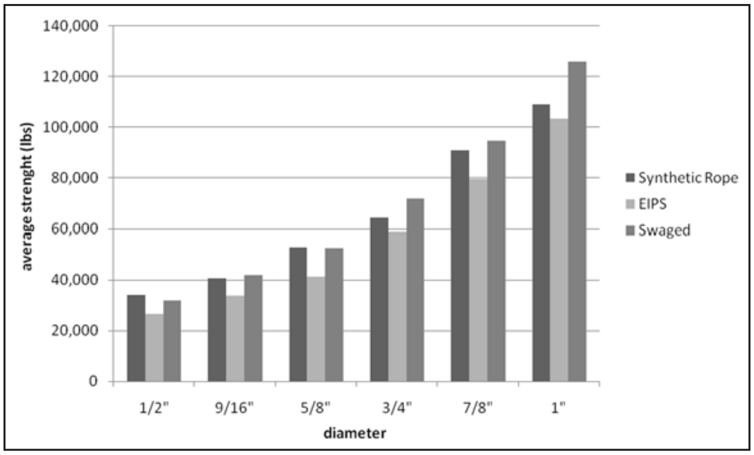

Figure 2.—Strength per foot of logging wire rope and UHMWPE synthetic rope at commonly used diameters.

wire rope is used in the Appalachian region. In the West there are many more activities where wire rope is used, such as in skyline and high lead logging systems.

Informal interviews with loggers and foresters working with logging contractors illustrated some initial hesitation to use the rope. While this reluctance is not unexpected, continual support and successful trials will be required to encourage broader use. Each of the five loggers interviewed said that pulling the wire rope uphill was the most difficult part of skidding activities, which is exacerbated when the slopes are steep and cover long distances. As expected, most responses also indicated that any decrease in work would be very desirable. Other concerns that were identified with existing wire rope were the inflexibility of the rope and the sharp wires that often are present with broken strands. Although most loggers wear leather gloves, the chance for puncture wounds to the hands and other body parts are high, especially when the rope must be pulled around obstacles. Each of these responses supports the adoption of UHMWPE rope as a potential method to minimize some of these issues.

Also collected during the interviews was the diameter of the wire rope each logger used, so as to select an appropriate UHMWPE rope diameter. Diameter to diameter the wire and synthetic ropes have very similar breaking strengths (Fig. 2). A smaller-sized dozer typically had 100 feet of 5/8-inch wire rope and used chain slides and chokers. Pilkerton and others (2004) reported that more UHMWPE rope than wire rope can often be accommodated because of synthetic rope's improved spooling and compaction.

UHMWPE rope distributors were identified in our region and through the Internet, and a 125-foot length of 5/8-inch UHMWPE rope was purchased for $4.26 per foot, about twice as expensive as wire rope. Additional rigging materials such as a splicing kit, slides, and chokers were also purchased for this study. The rope was installed on an older John Deere 450C bulldozer usually used for log skidding and road construction/clearing activities. The equipment and operators were provided by the West Virginia University (WVU)Research Forest. An eye splice was created that looped through the catch on the winch drum to affix the end of the rope to the spool. The rope was then spooled onto the drum under light tension in order to have a compact and well formed spool. While there were few if any rough metal places on the drum or other pieces of this winch system, grinding down any burrs or rough spots could help minimize damage of the rope by the winch.

Two different logging operations were tested with the rope. The first operation was a log skidding in a recovery operation, in which hardwood trees were felled away from a power line right-of-way. The trees to be extracted were often >20 inches in diameter at the stump, 30 to 40 feet in length, topped, and delimbed on three sides of the tree. Most trees were not positioned to lead, increasing the extraction difficulty. The ground surface in this area was very rocky and there were many stumps, slash, and other obstacles that the rope would have to work around. Four chain chokers and slides were strung on the UHMWPE rope, with the last one secured with an eye splice in the rope.

The rope performed flawlessly on this operation, providing no noticeable difference in strength or abilities than the wire rope that was used previously. The first few logs that were pulled stretched the rope out and allowed the spool to become more compact, but the rope did not dive in on the spool, where extra effort would have been required to remove it. One concern was that the UHMWPE rope was not as easy to pull off the winch drum as was expected, probably because it is hard to adjust the free spool of the winch. On this particular machine the adjustment for the free spool is located under the skidding arch, so any adjustment would require the complete removal of the arch, a labor-intensive activity that was not completed for this case study. With a lighter-weight rope, the free spool setting could be adjusted to allow for easier spooling off the drum to the log to be choked.

The UHMWPE rope was also used for a second job during this trial during a road clearing operation, in which very similar results were obtained. While the trees were slightly larger and on more of a slope (approximately 20 percent and less rocky soils), the rope performed well. The equipment operators were impressed with the strength, ease of working and splicing, and the rope's light weight.

DISCUSSION

Loggers can convert to UHMWPE rope without much effort. Very few adjustments to the usual practices are required as the UHMWPE rope performs in a manner very similar to the customary wire rope. In most cases, the logger would find some immediate advantages with the synthetic rope in winding the rope onto the drum as spooling can be done very quickly with almost no additional equipment. They will also find that splicing and hooking up rings, sliders, and other rigging pieces will be very simple. Many times during the first days of use, loggers will probably say, "I could never do that with the wire rope," as they carry the entire length over to the machine, or pull the rope through the woods to each log choker. Splicing the rope is one new step that loggers must master as they make the switch, but they can learn how in a manner of minutes and with very little practice.

As this project was a single case study, the results and identified applications may or may not be applicable to other operations in the region. The favorable results from the use of the rope convinced the loggers at the WVU Research Forest to keep the rope on the machine and continue using it in their operations. Long-term use of the rope and the longevity of the rope in comparison to wire rope will need to be further studied. Given the very similar results of this trial to research completed in the Northwest United States, we can expect a similar product life. Hartter (2004) notes that while UHMWPE rope cannot endure many of the types of abuse that steel rope withstands, a failed rope can be quickly respliced in the field. Additionally, many of the failures reported in the western U.S. studies were a result of abrasion from rough pieces of metal on the winch or other part of the equipment. New equipment or care in smoothing all metal surfaces that the rope comes in contact with, can minimize these failures. In this single study, abrasion with logs, soil, and other natural objects in the Appalachian forest had little impact on the rope other than discoloring it. While the more abrasion the rope is exposed to, the shorter the working life, this characteristic also applies to wire rope. After the case study had ended, the loggers reported that following 3 months of use, the eye splice that held the chain choker broke. After cutting the end off clean and resplicing the eye, they were back logging in just minutes.

Based on this case study, further dissemination of UHMWPE rope for test applications in logging should be continued. This study was limited in its scope but points to the need for scientific research regarding the operating life, use of different connecting techniques to the winch, and interactions with chokers and slides or rings. Given the current level of use and research on the topic, any logger converting to UHMWPE rope would still be considered an early adopter. We would expect operators to find valuable improvements in their operations that could possibly outweigh the risk involved with trying something new.

ACKNOWLEDGMENTS

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SOURCES OF THE INDIANA HARDWOOD INDUSTRY'S COMPETITIVENESS

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Abstract.—The estimated 1,600 forest products-related firms in Indiana employ more than 56,000 workers. Hardwood manufacturers are the largest segment, adding approximately $2 billion per year of raw product value. A recent report by BioCrossroads ranked the hardwood industry as the most important in the agricultural sector in Indiana. Like most of the other forest products manufacturers, the hardwood manufacturers have lost a sizable market share to imports and substitutes. To improve their performance in both the local and global markets, the Indiana hardwood manufacturers must have a clear understanding of how to assess their competitive position. This paper argues that to better understand the factors affecting competitiveness in this industry, research is needed that combines technology and economic analyses of competition. We review existing information on the performance of the Indiana hardwood industry and summarize current models regarding competitiveness and its sources. A review of the literature suggests that both internal and external market and government policy factors affect firm and industry competitiveness, yet these factors are rarely linked in a comprehensive analysis.

INTRODUCTION

Today's firms have realized the importance of involving all the stakeholders in making strategic decisions in order to compete both locally and globally. According to Porter (1980) the competitiveness of a firm is its ability to increase real income by utilizing its competencies to produce high quality goods and services that meet the test of world markets. These competencies include production technologies, supplier relationships, improved supply chain, improved quality control, employee expertise, and new product designing.

The introduction of free markets to accommodate some of the low-cost countries has changed how competition is viewed. Previously competition was viewed as stationary, and accomplishments or failures depended on production factors. Now competition is viewed as a dynamic process with many firms investing in new products, going to new markets, and adopting new technologies and management concepts.

The hardwood industry is no exception. According to a recent study by BioCrossroads (2005), the hardwood industry in Indiana was identified as the most important sector when it was benchmarked with other manufactured agricultural-based products in the State. According to the report, the hardwood industry represents a 31.4 percent employment share of the top nine sectors and 28.17 percent of the total growth. Despite this standing, the industry has lost approximately 17.3 percent of its jobs in the last 5 years. This study reviews existing information on the performance of the Indiana hardwood industry and summarizes current models regarding competitiveness and its sources.

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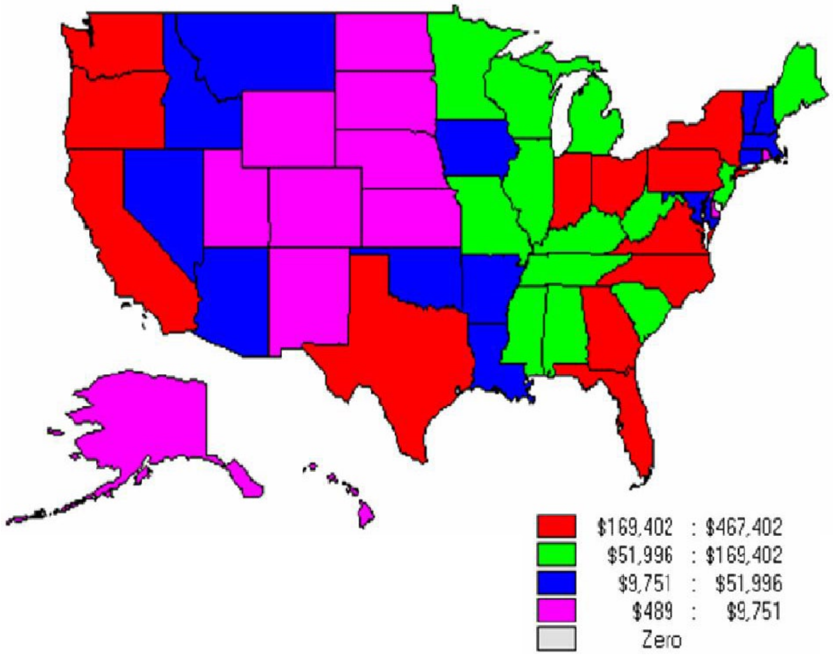

Figure 1.—The 2006 hardwood products exports to the world (by value and state; source: National Trade Data via web- http://tse.export.gov).

U.S. HARDWOOD INDUSTRY

The hardwood industry is composed of small, family-owned businesses. About 71 percent of hardwood growing stock on U.S. timberlands is owned by nonindustrial private landowners. Hardwood growth exceeded removal by 42 percent between 1996 and 2005 (U.S. Census Bureau 2005).

This industry plays a significant role in the U.S. economy. Estimates for U.S. hardwood lumber consumption in 2005 were more than 11 billion board feet (U.S. Census Bureau 2005). The major consumers of hardwood lumber are mostly value-added producers who manufacture such products as furniture, pallets, cabinets, millwork, and flooring.

Indiana was among the 12 leading exporters of hardwood products (Fig. 1), although in comparison of the total production volume of hardwood lumber per state Indiana was ranked 15th. We conclude that based on the production volume and export data Indiana's hardwood products must be either considered of better quality or have a certain competitive advantage. Most of the hardwood firms are located in the southern part of the state, close to the forest resource.

CONCEPT OF COMPETITIVENESS

Studies in competitiveness can be divided into descriptive and analytical approaches (Oral 1993). The descriptive approach provides a checklist of factors on general competition and strategic implications, while analytical approaches are based on models whose solutions provide insights for strategy formulation. Oral (1993) provides an example of an analytical approach study. He proposed a model to examine industrial competitiveness, and the phase-to-phase implementation in a large glass-making company. The competitiveness of the firm was expressed as a function of two major factors: industrial mastery and cost superiority. Industrial mastery indicated firms successes compared to competitors in terms of generating and operating capital and operational resources. Other studies where a model-based approach has been used are Sinha (1996) and Parkan (1994).

In the wood industry, model-based approaches have been used in several studies. Rich (1986) studied the competitive strategies of large wood-based firms. His sample included 42 of the largest U.S. corporations whose primary business was wood-based products. Corporations were classified by Porter's (1980) overall cost leadership, differentiation, or focus generic strategy types. Rather than infer overall corporate strategy from measurements of various strategic dimensions, Rich had respondents indicate directly which generic strategy type their company employed. Results showed that the majority of firms reported utilizing an overall cost leadership strategy. However, there was a trend toward the use of differentiation and focus strategies when compared with earlier results (Rich 1979). Another model-based study was by Cleaves and O'Laughlin (1986), who examined business-level strategy within a sample of 24 southern pine plywood producers. Fourteen variables were measured for each of the 24 companies, and a hierarchical clustering algorithm was used to define five strategic clusters.

Most wood industry studies based on descriptive approaches focused on structural characteristics such as the number of companies, output, productivity, raw material use, and market and market served (Bush and Sinclair 1989, Cardellichio and Binkley 1984, Spelter and Phelps 1984, and Wengert and Lamb 1980). Our study is intended to supplement these studies in addition to determining the hardwood industry's sources of competitiveness using a descriptive method.

SOURCES OF COMPETITIVE ADVANTAGE

A firm is said to have a competitive advantage if it has access to a resource or service that its competitors do not have. In a similar way the competitive advantage of an industry in a particular location is based on factors such as location advantage, resource proximity, and well established transportation network. These factors are made of various components which differentiate industries in one locality from the other. In this study five main factor components are analyzed in relation to the hardwood industry in Indiana: value creation, nature and scope of the market, internal sources of advantage, competitive strategy, and economics. A detailed analysis of each component is offered in Tables 1 through 5 in the Appendix.

Value Creation

The concept of value creation (chain) categorizes all the value-adding activities in a firm. The activities include inbound logistics, production, outbound logistics, marketing and sales, and services. For the hardwood industry the value chain will be composed of loggers (inbound), secondary manufactures, lumberyards, exports, construction (outbound) and marketing, sales and services (Fig. 2). In our study we will look only at the inbounds and outbounds. For firms to perform well, the inbounds and outbounds should be in balance, meaning that a manufacturer has to have a good control on both.

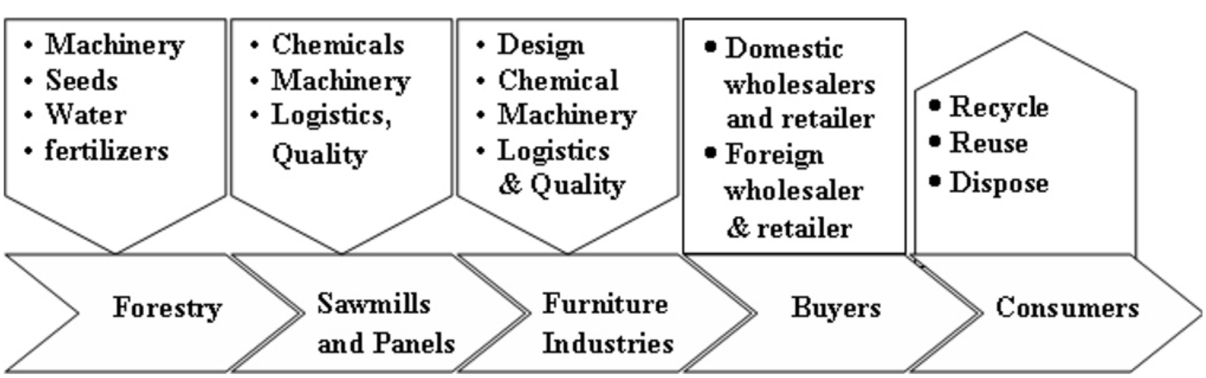

Figure 2.—Wood industry value chain.

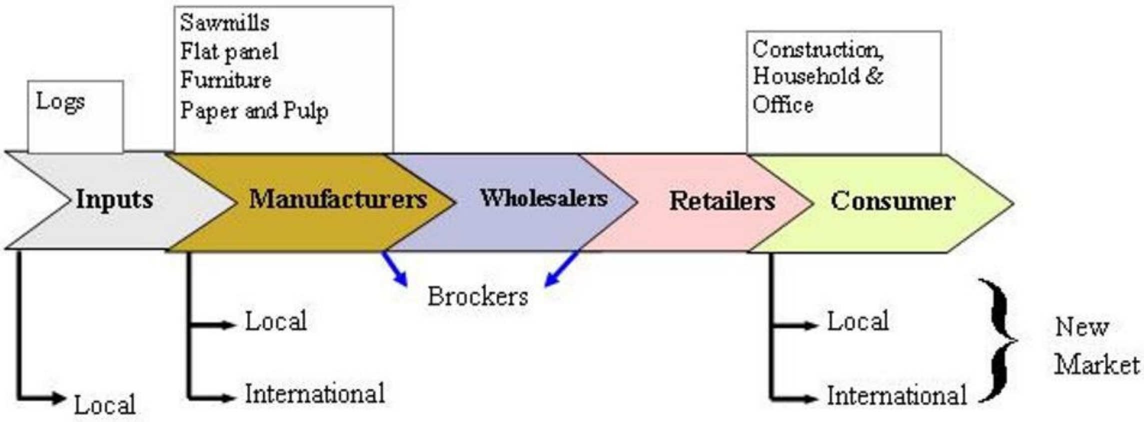

Figure 3.—New market.

For the hardwood industry the logs, which make up the highest percentage of the inbounds, usually vary in terms of price, species, source, and quality. Price is determined by the other three factors and market conditions. The type of species is also based on market demand and most manufacturers base their next production on historical data to determine which species is in demand. The logs can either be sourced from a government-managed forest or from individuals and families. Individuals and families usually have an incentive to manage for long-term sustainable benefits. Well managed forests usually imply increased quality and quantity, which lead to a competitive advantage. In Indiana about 85 percent hardwood forests are small and privately owned (Bratkovich and others 2003). The principal species found in these forests are walnut, oaks, hickories, ash, maples, and yellow-poplar.

Outbound includes furniture, pallets and boxes, building material, and exports. Outbound varies in terms of price, species, grade, and moisture content. Price is also determined by the other named factors. Competitive advantage can be gained through more efficient planning of the supply chain, better demand forecasting and improved control of the manufacturing processes. In Indiana, university and hardwood manufacturers collaborate to develop better manufacturing technologies that will lead to a competitive advantage. An example of this collaboration in an ongoing project involving log optimization through infrared scanning.

New markets are being developed along the value chain through the trade organizations (Fig. 3). These new markets will ensure that the hardwood manufacturers remain competitive.

Nature and Scope of Market

The nature and scope of the market are determined by looking at products, manufacturing, and distribution. In the case of the hardwood industry, lumber and other products can be differentiated through type of species, seasoning schedule, and type of sawing. What is demanded is usually determined by the market forces and trends. The sizes of lumber are standard, but firms gain competitive advantage through producing varying quantities of different sizes.

Manufacturing for most wood industries is internal and narrow lined, which means that there is limited flexibility in changing the structural layout of the manufacturing plant. But competitive advantage can be gained through technological advancement or adopting some of the successful production processes.

A good example is computer numerical controls, which when added to a manufacturing line and fully utilized to its full potential can lead to improved performance.

Distribution can be either single or multi-channeled. Based on our analysis hardwood industry firms usually have multiple distribution channels.

Internal Sources of Advantage

Indiana's hardwood industry has internal sources of competitive advantage through production technology, selling and marketing, resource leverage, networking, and supply chain management. A number of initiatives from the government, research institutions, and trade organizations are enhancing the industry's competitiveness.

CHALLENGES FACING THE HARDWOOD INDUSTRY IN INDIANA

Among the various challenges facing Indiana's hardwood industry are: labor, environment, international trade practices, quality inputs, transportation, and research and development.

The number of people working in the hardwood industry has been declining since 2001. This decrease can be attributed to the imports and substitutes that have driven the price of products down, thus affecting the economies of scale. The uncertainty in the job market in this sector has driven some of the experienced and best qualified workers to other industries with greater job security. The influx of imports and substitutes, coupled with the departure of experience employees, will reduce the firms' competitiveness.

Availability of quality input is another major concern to industry practitioners. Most of the hardwood forests in the State are individually owned, so it is very hard for manufacturers to determine with certainty the quality of logs they will get.

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APPENDIX:
COMPONENTS ANALYSIS OF THE HARDWOOD INDUSTRY IN INDIANA

Table 1.Value creation (factors related to offering)

Factor	Primary wood industry
Organization	Business to Business
Sales point	Local Regional (Majority) National International
Customer in value chain	Down stream: loggers, machinery Up stream: builders, suppliers, value-adding manufacturers
Market	Broad
Business dealing	Transactional

Table 2.—Nature and scope of market

Offering	Primary wood industry
Products	Primary wood products from logs
	Standardized
	Sold by itself
Manufacturing	Internal
	Narrow lines
Distribution	Indirect multi-channeled

Table 3.—Internal source of advantage

Production technology
Selling and marketing
Resource leverage
Networking
Supply chain management

Table 4.—Competitive strategy factors

Factor	Primary wood industry
Image of operational	Consistent Dependability Speed
Product / service	Quality Features Availability
Cost versus efficiency	Efficiency

Table 5.—Economic factors

Factor	Primary wood industry
Pricing and revenue sources	Fixed mixed
Operating leverage	medium
Volumes	High
Margins	High Medium

ECOLOGY AND FOREST DYNAMICS

LONG-TERM LEAF FALL MASS FROM THREE WATERSHEDS ON THE FERNOW EXPERIMENTAL FOREST, WEST VIRGINIA

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Abstract.—Foliar biomass may serve as an indicator of site productivity, and spatial and temporal changes can help us understand effects of important variables affecting productivity. Leaf litterfall mass is one way to estimate foliar biomass, and has been measured on three watersheds on the Fernow Experimental Forest in West Virginia for 19 years. These watersheds all contain Appalachian mixed hardwood stands. The hardwood stand on watershed 4 (W4) has been untreated since around 1910 and serves as the primary reference watershed for the Fernow. The stands on watersheds 3 (WS3) and 7 (WS7) regenerated from clearcuts in 1969-1970. Using 25 litterfall traps per watershed, annual leaf fall mass has been determined since 1989 (WS3, WS4) or 1991 (WS7). Leaf fall mass is greatest on WS4 over time. Despite the addition of 35 kg of nitrogen per ha each year since 1989 to WS3, there is no statistically significant difference in litterfall mass between the two young stands (WS3 and WS7).

INTRODUCTION

Uncertainty about the effects of acidic deposition on forest health and productivity continues to be an issue of concern for forest managers and scientists. There is evidence that acidic deposition may affect soils in some forest types, with implications for health of those forests, most notably red spruce in the northern Appalachians and Adirondacks (Eagar and Adams 1992, DeHayes and others 1999), and sugar maple in some parts of the northeastern U.S. and Canada (Horsley and others 2000, Duchesne and others 2002). Acidic deposition impacts on aboveground productivity have not been well documented in other eastern forest types, however, and ongoing research into effects of acid deposition on forest soil properties and processes continues to be relevant and critical.

The Fernow Watershed Acidification study was begun in 1988, with the objective of determining the impacts of atmospheric deposition on forest ecosystems by determining changes in solution chemistry, particularly soil leachate and stream water chemistry (Adams and others 2006). Since 1989, we have been adding 35 kg N/ha/yr and 40 kg S/ha/yr as ammonium sulfate fertilizer, applied three times per year to the treatment watershed. The scope of the study has expanded over the years, and considerable effort has been made to identify effects on productivity of the forest resulting from soil chemical changes. Measurements of forest productivity, however, are often less sensitive to atmospheric deposition than are soil and water chemistry (Reed and others 1994).

Leaf area is related to the productivity of a forest stand through the mechanism of photosynthesis; leaves are the primary producers of energy for trees. Because of this link, foliar biomass may be one indicator of productivity of forest stands, and it can be easily estimated by determining the amount of leaf shed over the course of a year. Particularly in deciduous stands, this estimate can be easily made with a reasonably high degree of confidence (Lloyd and Olson 1974) by sampling autumn leaf fall. We have been monitoring leaf fall mass since 1988 as part of the Fernow Watershed Acidification Study (Adams and others 2006); here we present the results of this long-term monitoring effort. We hypothesized either an increase in leaf fall

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Table 1.—Some characteristics of the study watersheds. Stand parameters are based on the 1990 inventory for watershed 4, 2004 for watersheds 3 and 7

	Watershed 3			Watershed 7			Watershed 4		
Area (ha)		34			24			39	
Aspect		South			East			Southeast	
Mean elevation (m)		792			792			792	
Stand age in 2007		37			37			97	
Mean stand density (stems ha^{-1})		1883			1473			1206	
Mean stand basal area (m2 ha^{-1})		36.0			28.0			38.6	
Mean stand biomass (mt ha^{-1})		203.4			157.5			310.65	
Dominant tree species (stems ha^{-1}) (% basal area)	Black cherry	442	(51.0)	Sugar maple	334	(4.9)	Sugar maple	336	(11.3)
	Red maple	366	(11.5)	Sweet birch	319	(20.5)	Red maple	188	(8.9)
	Am. beech	245	(2.5)	Red maple	274	(8.2)	Am. beech	183	(6.5)
	Sweet birch	161	(5.1)	Yellow-poplar	143	(26.2)	N. red oak	69	(29.8)
	Sugar maple	119	(1.3)	Black cherry	143	(20.5)	Sweet birch	42	(3.6)

mass, as a result of the increased nitrogen availability resulting from the repeated application of a fertilizer containing nitrogen, or perhaps a decline in leaf mass as the soil acidified and base cation depletion occurred. Our larger objective was to find a simple, reliable signal to detect productivity changes resulting from acidic deposition.

SITE DESCRIPTION

The three watersheds that have been monitored as part of the Fernow Watershed Acidification study are located on the Fernow Experimental Forest (FEF) in north central West Virginia (39.03° N, 79.67° W), in the Allegheny Mountain section of the mixed mesophytic forest (Braun 1950). The growing season of the FEF extends from May through October and the average length of the frost-free season is 145 days. Annual precipitation is evenly distributed between growing and dormant seasons, averaging 145.8 cm. The average annual air temperature is 9.2 °C. Soils are acidic, derived from acid sandstone and shale, and about a meter in depth (Kochenderfer 2006).

Forests on the FEF are predominantly deciduous hardwoods, with a high diversity of tree species. Dominant tree species include black cherry (*Prunus serotina*), yellow-poplar (*Liriodendron tulipifera*), sugar maple (*Acer saccharum*), and northern red oak (*Quercus rubra*), among others (Table 1). The stands on these three watersheds have different treatment histories as part of long-term research on the FEF. Watershed 4 (WS4), which serves as the main long-term reference watershed on the FEF, has been undisturbed since around 1910, when much of eastern West Virginia was logged for the first time (Kochenderfer 2006). Watershed 3 (WS3) originally received an intensive selection cut in 1958-1959, and then was harvested in a series of patch clearcuts in 1968-1969. Watershed 7 (WS7) was clearcut and maintained barren with herbicides between 1963 and 1969. Both WS3 and WS7 regenerated from natural regeneration sources beginning in the winter of 1969/1970. WS3 was then selected in 1988 to serve as a treatment watershed for the Fernow Watershed Acidification Study. Since 1989, WS3 has received approximately 35 kg N/ha/yr and 40 kg S/ha/yr as ammonium sulfate fertilizer, applied 3 times per year. For water chemistry and hydrologic purposes, WS4 is the reference watershed in the Fernow Watershed Acidification Study. However, because of the differences in stand age between WS3 and WS4, we decided that information should also be collected from WS7, where the trees are the same age as in WS3. Further information about the three watersheds is shown in Table 1, and can be found in Kochenderfer (2006).

METHODS

Twenty-five litterfall traps (91 cm x 91 cm x 10 cm deep) were randomly located on each of the three forested watersheds. Each autumn, beginning in 1988, the leaves from these traps are collected in plastic bags and returned to the lab for drying and weighing. Approximately weekly collections are made throughout the autumn (generally three to five collections per year), until all of the leaves appear to have fallen. The leaves in each litter trap are dried to a constant mass in a 60 °C oven, and the mass recorded. Litter traps are cleaned before leaf fall each year, and only leaf fall into the traps is collected (i.e., no large or small woody debris; seeds are not excluded). Total leaf dry mass is determined for each litterfall trap, and then a total value estimated for each stand. Because of the high species diversity and the large effort involved in separating leaf litter by species, the total leaf fall mass was determined across all tree species. Also, Lloyd and Olson (1974) reported that while this method provides precise estimates of annual leaf fall mass for mixed hardwood stands, it does not appear to be particularly good for estimating annual leaf fall mass of individual tree species.

Means and standard deviations were calculated for each watershed for each year, and means were compared between each pair of watersheds using t-tests (WS3 vs. WS4, WS3 vs. WS7, WS7 vs. WS4), with comparisons made at the 0.05 level of significance. Data were analyzed using linear regression techniques to examine trends within watersheds over time, and to evaluate relationships with growing season precipitation amount.

RESULTS AND DISCUSSION

Annual leaf fall mass ranged from 1.92 Mg/ha (WS7, 2000) to 5.57 Mg/ha (WS4, 2004), with considerable year-to-year variability (Table 2). Leaf mass on WS7 (coefficient of variation of 14 percent)was slightly more variable from year to year than WS4 (11.6 percent) and WS3 (910.6 percent). These values approximate the range described by Jenkins (2002) of 2.5 to 5.4 Mg/ha/yr for Central Hardwood forests. Kochenderfer and Wendel (1983) reported a much narrower range, from 3.94 to 4.68 Mg/ha/yr over a 4-year period for stands on north- and south-facing slopes on the FEF. In general, the stands evaluated by Kochenderfer and Wendel (1983) were second-growth stands, comparable in age to the stand on WS4. Leaf fall mass was consistently greatest on WS4, the oldest of the three stands. WS4 was also the stand with the highest aboveground biomass, suggesting an age or biomass effect. Stands with greater aboveground biomass are likely to produce more leaf area than those with less biomass. Muller and Martin (1983) compared old-growth and second-growth (approximately 45 yrs old) forests in eastern Kentucky and found no significant difference in total leaf fall between the two stands, averaging 2.91 Mg/ha. Note, however, in that study the basal area did not differ between the two stands, and was equal to that of the WS7 stand in our study (~29 m^2/ha). Thus stand biomass may not have varied greatly between the two Kentucky stands. The authors reported the two stands were similar in species composition as well.

The interannual variability (annual cv range = 9.3 percent to 28.6 percent) was not significantly related to growing season precipitation amount (for WS4 r^2=0.1172 p=0.2117) to total annual precipitation (WS4: r^2=0.0728, p=0.3308), nor did it appear to be related to specific large disturbances such as windstorms

Table 2.—Annual leaf fall dry mass from three watersheds on the Fernow Experimental Forest

year	WS3	WS3 std.dev	WS7	WS7 std.dev.	WS4	WS4 std. dev.
	Mg/ha					
1988	3.33	0.31			4.2	0.69
1989	3.19	0.50			3.89	0.69
1990	3.02	0.57			3.56	0.53
1991	3.31	0.57	3.31	0.47	4.21	0.53
1992	3.41	0.40	3.08	0.52	4.19	0.99
1993	3.19	0.37	3.01	0.56	3.82	0.76
1994	3.21	0.47	3.09	0.61	3.60	0.60
1995	3.11	0.39	3.32	0.57	4.35	0.68
1996	3.05	0.54	3.00	0.49	4.38	1.12
1997	2.15	0.37	2.35	0.45	3.61	0.67
1998	2.67	0.51	2.98	0.65	3.92	0.82
1999	2.84	0.34	2.89	0.42	3.96	0.50
2000	2.86	0.41	1.92	0.40	3.68	0.51
2001	3.22	0.40	3.71	0.55	4.59	1.21
2002	2.92	0.30	3.10	0.44	4.04	0.48
2003	3.35	0.43	3.44	0.40	4.50	0.60
2004	2.91	0.57	3.25	0.49	5.57	1.43
2005	3.63	0.43	3.49	0.46	4.35	0.86
2006	2.89	0.41	3.36	0.96	3.70	0.68
mean	3.06		3.08		4.11	
std.dev.	0.32		0.43		0.47	
coefficient of variation	10.6%		14.1%		11.6%	

and ice storms which significantly affected the canopy (Adams and others 2003; Fig. 1). Burton and others (1991) reported that they could not attribute changes in litter production to an acid deposition gradient because of year-to-year variability resulting from insect defoliation and seed production.

Leaf fall mass was significantly greater on WS4 than on WS3 or WS7, but the differences between WS3 and WS7 were generally not statistically significant. This result suggests that the acidification treatment has not significantly increased leaf production on WS3 as a result of increased nitrogen availability. We might have expected an increase in foliar biomass over time on WS3 and WS7 as younger trees are generally more capable of utilizing available N. Significant increases in foliar nitrogen concentrations were observed for some tree species in the early years of the fertilization treatment (Adams and others 2006), which provides support for this hypothesis. In addition, there was an initial positive volume growth response to the fertilizer additions (DeWalle and others 2006), providing support for the idea of a short-term increase in productivity due to increased nitrogen availability. This fertilizer effect was not sustained, however, either in terms of nutrient concentrations or aboveground growth (Adams and others 2006, DeWalle and others 2006). Therefore, we conclude that an apparent effect of the fertilizer on leaf fall biomass was not detected, either as a difference between WS3 and WS7, or as an increase or change in litter fall mass over time for WS3. None of the watershed regression lines shows a statistically significant trend over time (Fig. 2). The

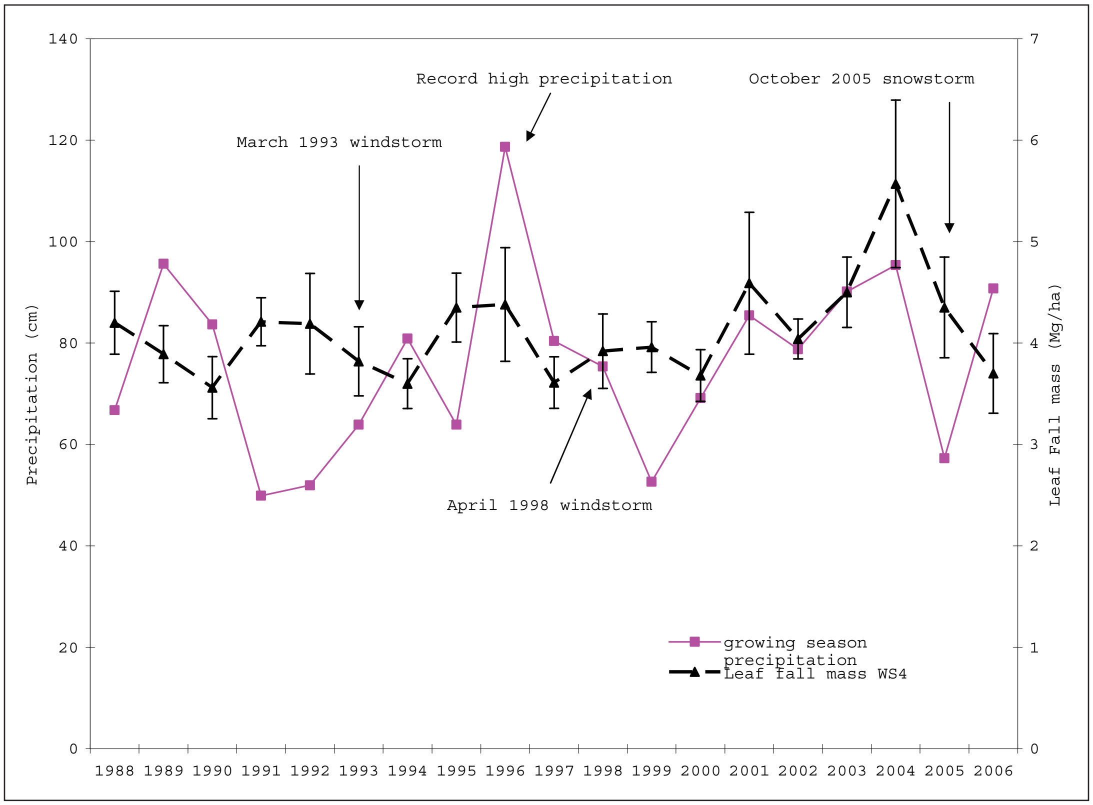

Figure 1.—Leaf fall mass (Mg/ha/yr) and growing season precipitation (May 1-October 31) from watershed 4 on the Fernow Experimental Forest. Significant climatic events which could affect leaf fall mass are indicated (Adams and others 2003.)

effect may have been short-lived, perhaps due to increasing competition among the young trees because of high stand density, or perhaps due to another nutrient limitation (phosphorus or possibly calcium). We have some evidence to suggest that phosphorus may be limiting the volume growth of black cherry on WS3 (Adams and others 2006).

Similarly, a decline in leaf biomass which might be attributed to the cumulative acidification effects of the treatment was not demonstrated. Such a decline might occur if soil acidification processes adversely affected productivity. There is some evidence from soil solution chemistry of mobilization and decline of calcium (Edwards and others 2006), although exchangeable soil calcium levels did not significantly change (Adams and others 2006). The mobilization and depletion of calcium is reflected in a relatively limited sample of tree rings, both in radial growth and dendrochemistry (DeWalle and others 2006), but does not show up as a statistically significant effect in leaf fall mass. Although the slope of the regression line for WS3 is negative (Fig. 2), the trend is not statistically significant.

Other studies of fertilizer effects on hardwood forests have shown relatively few effects on foliar mass or leaf fall. Kochenderfer and Wendel (1983) reported no statistically significant effects of a single addition of 336 kg N/ha on leaf fall biomass on either north- or south-facing watersheds containing second-growth hardwood forests. Other researchers working in similar central Appalachian hardwood stands (Auchmoody and Smith 1977), reported slight increases in foliar mass of yellow-poplar and northern red oak as a result of fertilization, but these differences were not statistically significant, although foliar chemistry was significantly altered by the treatment.

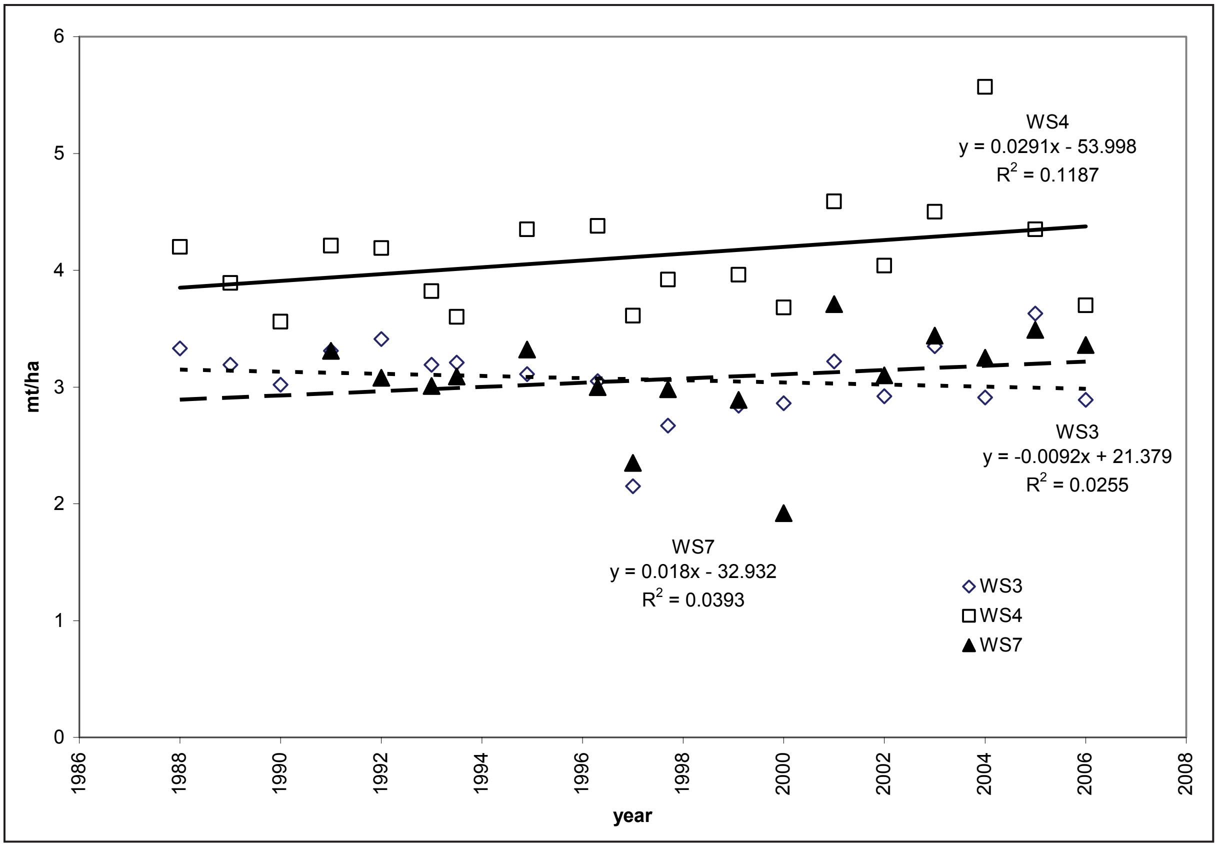

Figure 2.—Leaf fall mass (Mg/ha/yr) from three forested watersheds on the Fernow Experimental Forest, with linear regression trend lines and statistics.

In general, our results suggest that leaf fall biomass is relatively nonresponsive to site quality, except perhaps as mediated through effects on overall biomass, as neither fertilization treatments nor differences in precipitation amount significantly altered the annual leaf fall mass in these stands. It is possible that the fertilization treatment, while having other ecosystem effects, may not have been a sufficiently large amount of nitrogen to create the hypothesized response. Conversely, the significant interannual variability in leaf fall mass may have masked any treatment effects. Finally, the response of leaf area and mass to fertilization is complex, and any initial effect may have diminished over time. The Fernow Watershed Acidification Study is on-going, and fertilization treatments and monitoring are continuing. Further assessments of productivity, including continuing measures of leaf fall mass, will provide us with additional insights into the relationship between acidic deposition, soil fertility and forest productivity.

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DISTRIBUTION AND DYNAMICS OF HAYSCENTED FERN FOLLOWING STAND HARVEST

Songlin Fei, Peter J. Gould, Melanie J. Kaeser, and Kim C. Steiner[1]

Abstract.—The distribution and dynamics of hayscented fern were examined as part of a large-scale study of oak regeneration in Pennsylvania. The study included 69 stands covering 3,333 acres in two physiographic provinces. Hayscented fern was more widely distributed and occurred at higher densities in the Allegheny Plateau physiographic provinces versus the Ridge and Valley region. After partial overstory removal, the density and distribution of fern increased in stands that were not treated with herbicide. Herbicide treatments successfully reduced fern densities and created a 'window of opportunity' about 4 years post-harvest for the establishment of regeneration.

INTRODUCTION

In the mixed hardwood forests of Pennsylvania, dense groundcover of hayscented fern (*Dennstaedtia punctilobula* (Michx.) Moore) and other herbaceous species interfere with the development of advance regeneration of oaks (Horsley and others 1992, Steiner and Joyce 1999). Regeneration of tree seedlings may be adversely affected due to hayscented fern's ability to influence the availability of light, nutrients, and water (Messier et al. 1989, Lyons and Sharpe 1996, George and Bazzaz 1999, Engelman and Nyland 2006). Hayscented fern has been classified as a competitor species because of its ability to respond aggressively to sudden resource availability by way of vegetation expansion of rhizomes and sexual reproduction through spore dispersal (Groninger and McCormick 1991, Hughes and Fahey 1991).

Hayscented fern's ability to occupy a variety of habitats makes it a dominant component of the understory in various regions throughout Pennsylvania. Small-scale studies have shown that hayscented fern is a large component of the groundcover in relatively productive oak stands (Allen and Bowersox 1989) and on poorly drained soils (Marquis 1979). There is limited information about the distribution of hayscented fern among other forest community types, however, previous studies have focused on only one or several stands and failed to look at landscape-level patterns of fern colonization. Yet in light of the oak regeneration problem facing forest managers in Pennsylvania, the distribution and dynamics of this competing species need to better understood (McWilliams and others 1995). This paper focuses on the distribution of hayscented fern at a landscape scale in Pennsylvania, and articulates its response to overstory removal and herbicide treatments.

STUDY AREA

The study area crosses the Allegheny Plateau and Ridge and Valley physiographic provinces of Pennsylvania (Fig. 1). Soils in both provinces in stands represented in this study are derived from sandstone, siltstone, and shale and are typically well drained and support moderately productive forests. Stand elevations range from 250 m above sea level in the Ridge and Valley province to 700 m on the Allegheny Plateau. Precipitation, temperature, and length of growing season vary with latitude and topography. Mean annual

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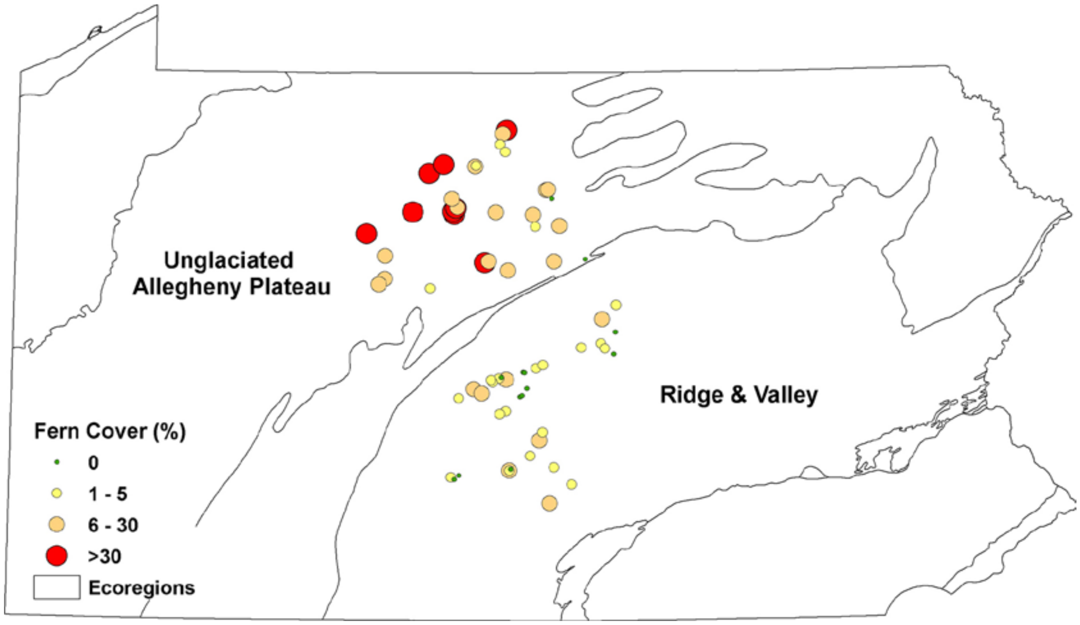

Figure 1.—Distribution of average hayscented fern cover in 69 Pennsylvania stands before harvest.

precipitation ranges from 960 to 1,070 mm and mean annual temperature ranges from 8 to 11 °C. The growing season ranges from 120 to 140 days in the northwest, and 140 to 180 days in the southeast.

METHODS

Data Collection

Field measurements in 69 stands in Pennsylvania were performed on a total area of 3,333 acres of state land during 1996 - 2006. Thirty-one stands were located on the Allegheny Plateau and 38 stands in the Ridge and Valley physiographic provinces. All the stands were measured 1 year prior to silvicultural treatment, 52 stands were remeasured 1 year after treatment, 43 stands were remeasured 4 years after treatment, and 17 stands were remeasured 7 years after treatment. Depending on stand area, 15 to 30 twentieth-acre permanent plots (26.3 ft radius) were systematically installed in a square grid to represent the whole stand. Four permanent milacre subplots (3.72 ft radius), were also set up within each plot. On each subplot, percentage cover of hayscented fern was estimated. In total, we measured 7,481 subplots before treatment, and remeasured 5,163 subplots 1 year after treatment, 4,240 subplots 4 years after treatment, and 1,715 subplots 7 years after treatment.

Treatments

Treatments were based upon the forester's management objectives for each stand and were not experimentally controlled. The primary objective of the treatments was to establish and/or release desirable regeneration. Overstory treatments ranged from 20 to 80 percent basal area reduction at the stand level. Stands were treated with herbicide if hayscented fern densities appeared likely to inhibit regeneration as judged by the staff forester in charge. OUST® (sulfometuron methyl) or an ACCORD®/OUST® mix was applied to dense hayscented fern at various rates depending on fern density. Herbicide was applied before the first remeasurement in 22 of the 31 stands in the Allegheny Plateau and four of the 38 stands in the Ridge and Valley physiographic provinces.

Table 1.—Stand-level average of hayscented fern by physiographic provinces and time of assessment

	Time	Fern Cover (%)	Fern Freq.[1] (%)	Dense Fern Freq.[2] (%)
Ridge and Valley	1yr-pre (n=38)	3.0	11.6	4.2
	1yr-post (n=29)	2.8	27.1	3.7
	4yr-post (n=25)	4.8	46.1	5.5
	7yr-post (n=13)	9.6	55.5	13.6
Allegheny Plateau	1yr-pre (n=31)	19.6	52.0	28.3
	1yr-post (n=23)	7.8	46.1	9.5
	4yr-post (n=18)	7.4	57.1	9.7
	7yr-post (n=4)	11.2	62.4	14.0

[1]Percentage of subplots with hayscented fern cover.
[2]Percentage of subplots with heavy hayscented fern cover (>30 percent).

Data Analysis

For each stand, average fern cover, percentage of subplots with fern, and percentage of subplots with over 30 percent fern cover were calculated. Percentage cover by hayscented fern was divided into four classes—none, low (1 to 5 percent cover), moderate (6 to 30 percent), and heavy (over 30 percent). The heavy class reflects the level of competing vegetation that was considered problematic by Marquis (1994).

Fern cover class transition rates from before harvest to 1, 4, and 7 years after harvest were calculated. Transition rates were calculated as the percentage of plots in a given pretreatment cover class that fell into each cover class 1, 4, or 7 years after harvest. Consequently, transition rates sum to 100 percent for each pretreatment cover class. Subplots in the Ridge and Valley and Allegheny Plateau physiographic provinces were combined, but transition rates were calculated separately for herbicided and non-herbicided subplots.

RESULTS

Average hayscented fern cover percentage ranged before treatment for all 69 stands were plotted on the Pennsylvania physiographic provinces map (Fig. 1). Generally, stands on the Allegheny Plateau had a higher percentage of hayscented fern cover than stands in Ridge and Valley. However, there were two stands on the Allegheny Plateau that had no fern cover, and seven stands in the Ridge and Valley had moderate fern cover.

Before overstory removal, Ridge and Valley stands had lower fern cover, frequency of occurrence, and frequency of heavy hayscented fern than the Allegheny Plateau stands (Table 1). Average percentage of hayscented fern cover for the Ridge and Valley stands remained nearly unchanged from one year before treatment (3.0 percent) to 1 year after treatment (2.8 percent), but increased 4 and 7 years after treatment (4.8 and 9.6 percent, respectively). Average frequency of subplots with the presence of hayscented fern in the Ridge and Valley showed a pronounced monotonic increase during the survey period. One year before treatment, 11.6 percent of subplots had fern cover, increasing to 27.1 percent 1 year after treatment, to 46.1 percent 4 years after treatment, and to 55.5 percent 7 years after treatment. Changes in the percentage of plots with heavy fern cover occurred in a pattern similar to the average percentage of hayscented fern cover.

The Allegheny Plateau stands had an average of 19.6 percent fern cover 1 year before treatment. Fern cover dropped to 7.8 percent 1 year after treatment and 7.4 percent 4 years after treatment (Table 1). The

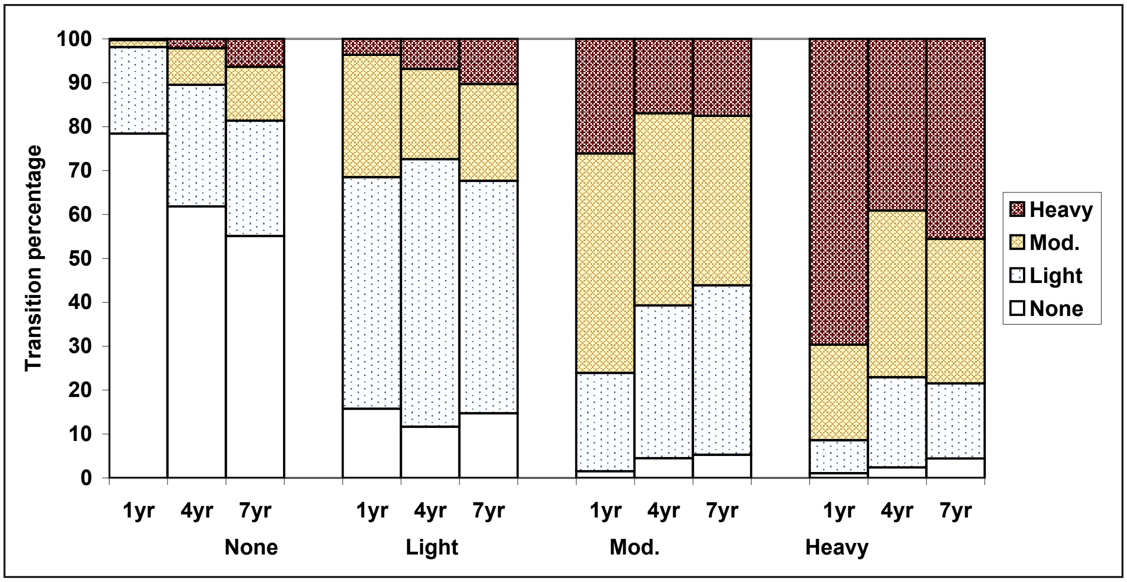

Figure 2.—Hayscented fern cover class transition percentages from 1 yr before harvest to 1, 4, and 7 yr after harvest without herbicide treatment (e.g. 78 percent of subplots classified as none cover class before harvest retained in the same cover class and 20 percent transited to the light cover class 1 yr after harvest).

decrease in fern cover was likely due to herbicide application as 58 percent of the stands were treated with herbicide after the first measurement. Fern cover recovered to 11.2 percent seven years after treatments. Percentage of plots with fern cover decreased slightly from 52.0 percent 1 year before treatment to 46.1 percent 1 year after treatment, but recovered and surpassed 4 and 7 years after treatment (57.1 and 62.4 percent, respectively). Changes in percentage of plots with heavy fern cover had a similar pattern to fern cover percentage.

Overstory removals without herbicide treatment resulted in an increase of fern after harvest throughout the survey period (Fig. 2). About 21.6 percent of subplots that had no fern cover before harvest moved into other fern cover classes 1 year after harvest. Four and 7 years after harvest, the percentage increased to 39.2 and 44.9, respectively. A considerable proportion of subplots that started in the light cover class moved into the moderate and heavy cover classes. Some reduction of fern cover density was observed on subplots that were classified as moderate or heavy fern cover classes. For subplots that had moderate fern cover before harvest, 23.9 percent fell into the light or no fern cover classes 1 year after harvest, and the percentage increased to 39.3 and 43.9 4 and 7 years after harvest, respectively. However, more than one-seventh of moderate fern cover subplots transitioned into heavy fern cover class throughout the post-harvest survey period. Less than 5 percent of the subplots that were classified in the heavy fern class fell into the no cover class after harvest. The overall trend is that stands without herbicide treatment after harvest had a spread of fern cover and increased density for subplots that had low or no fern cover before overstory removal.

Herbicide treatments in conjunction with overstory removals successfully reduced the cover of hayscented fern to non-problematic levels across all density classes (Fig. 3). One year after treatment, fern cover was absent or light on 86.9 percent of the subplots that started with heavy fern cover. Among all of the pretreatment cover classes, fern cover was light or absent in over 80 percent of the subplots. Four years after treatment, the recovery of hayscented fern from the herbicide treatment was evident. Furthermore, the pretreatment cover class influenced the level to which fern abundance recovered. More than one-tenth of the subplots that had heavy fern cover before harvest returned to that class 4 years after harvest.

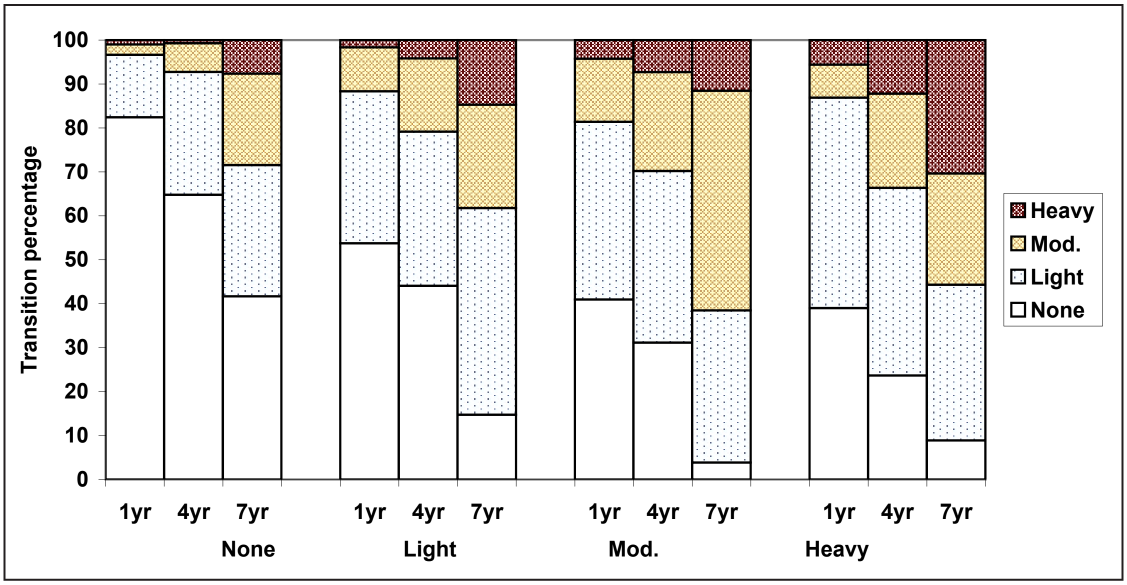

Figure 3.—Hayscented fern cover class transition percentages from 1 yr before harvest to 1, 4, and 7 yr after harvest with herbicide treatment (e.g. of all subplots classified as heavy cover class before harvest, 39 percent, 24 percent, and 9 percent transited to the none cover class 1, 4, and 7 yr after harvest, respectively).

An additional 7.3 percent of the subplots that had moderate pretreatment fern cover reached heavy fern cover by 4 years after harvest. The recovery of hayscented fern from herbicide treatment was even more pronounced 7 years after harvest. Over three-fifths of the subplots that had moderate fern cover before harvest returned to the moderate class or increased to the heavy class, and over one-half of the subplots that had heavy fern cover before harvest recovered to the moderate or heavy class 7 years after harvest.

DISCUSSION

Competition between tree seedlings and hayscented fern has been identified as a factor contributing to the oak regeneration problem in Pennsylvania (McWilliams and others 1995). Our results indicate that hayscented fern is more prevalent on the Allegheny Plateau than in the Ridge and Valley.

Without herbicide treatments, hayscented fern became more widely distributed and increased in density following partial overstory removal. Most of the stands in the Ridge and Valley were not treated with herbicide because hayscented fern was either absent or did not occur at problematic levels before harvest. After harvest, both the distribution and density of hayscented fern increased as a result of stand disturbance associated with overstory removal. However, hayscented fern did not reach problematic densities after 7 years in the Ridge and Valley because initial densities were low. In contrast, the distribution of fern in this region increased dramatically. It is uncertain whether this increase in distribution is a precursor to a greater fern problem in the future, or a short-lived phenomenon associated with overstory disturbance. The expansion of fern has the greatest potential to become a problem in stands that fail to regenerate quickly.

Herbicide treatments created a “window of opportunity” for the establishment of seedlings following partial overstory removals. One year after treatment, fern cover was reduced to non-problematic levels on most of the subplots with initially heavy fern cover. After 7 years, fern cover had partially recovered from the herbicide treatments, but less than one-third of the initially heavy fern cover plots had returned to that condition. Given that oaks are expected to produce large acorn crops every 4 to 6 years, the window of opportunity provides a chance to capture a regeneration cohort. A heavy mast year shortly after the herbicide treatment, or initially high levels of advance regeneration, should result in the successful establishment of oak regeneration (Johnson and others 1989). The rate of fern recovery between two consecutive surveys accelerated after treatments and a complete recovery is likely (Horsley and others 1992). If a mast year does not occur in the several years following the herbicide treatment, the window of opportunity will likely close as fern recovery accelerates.

Caution is needed when applying the findings to forest management practices. In our stands, we have different intensities of overstory removal, ranging from 20 to 80 percent. Although over 70 percent of the stands had at least 50 percent of their overstory removed, there might be a relationship between the rate or extent of fern spread after cutting, and the cutting intensity. Other factors such as forest community types might also influence the findings. Additional analyses of those factors may be needed in future studies.

CONCLUSIONS

- Hayscented fern is more prevalent on the Allegheny Plateau than in the Ridge and Valley physiographic provinces of Pennsylvania.
- Hayscented fern became more widely distributed and increased in density after overstory removal in stands that were not treated with herbicide.
- Herbicide treatments created a window of opportunity for the establishment of regeneration. After 4 years, fern recovery was accelerated and the opportunity to establish regeneration appeared to decline.

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SHIFTS IN RELATIVE STOCKING OF COMMON TREE SPECIES IN KENTUCKY FROM 1975 TO 2004

Christopher M. Oswalt, Jeffrey W. Stringer, and Jeffery A. Turner[1]

Abstract.—Changes in species-specific relative stocking indicate the extent to which a species is either increasing or decreasing in a particular system. Changes in relative stocking values of common tree species in Kentucky from 1988 to 2004 were compared to values calculated for 1975 to 1988. Mean annual increase in relative stocking between 1988 and 2004 was greatest for eastern white pine (*Pinus strobus* L.), boxelder (*Acer negundo* L.), and loblolly pine (*P. taeda* L.), averaging 1.29, 1.25, and 1.06 percent year-1, respectively. Species with an observed decline in relative stocking for both 1975-1988 and 1988-2004 include American beech (*Fagus grandifolia* Ehrh.), scarlet oak (*Quercus coccinea* Muenchh.), northern red oak (*Q. rubra* L.), post oak (*Q. stellata* Wangenh.), black oak (*Q. velutina* Lam.), black walnut (*Juglans nigra* L.), and chinkapin oak (*Q. muehlenbergii* Engelm.). Species with an observed increase in relative stocking over both periods include eastern redcedar (*Juniperous virginiana* L.), boxelder, red maple (*A. rubrum* L.), silver maple (*A. saccharinum* L.), and sugar maple (*A. saccharum* Marsh.). Results suggest that the *Acer* genus has greatly increased over the past 30 years while the *Quercus* genus has continually declined. These results support the generally accepted notion that the eastern deciduous landscape continues to experience replacement of oak with more generalist species such as red maple.

INTRODUCTION

Shifts in species composition herald changes in forest types throughout much of the oak/hickory forest type (e.g., Fei and others 2007). Typical of many states in the eastern United States, Kentucky maintains a high proportion of oak-hickory forests (Smith and others 2004) accounting for approximately 72 percent of the 11.6 million acres of timberland within the state (Turner and others In press). While forest inventory data suggest that the dominance of the oak-hickory forest type continues throughout Kentucky, there is evidence that significant changes in species composition are underway. However, high species diversity and numerous hardwood and softwood associates typical of the oak-hickory forest type are masking changes in species composition.

The degree to which species composition changes indicates the extent to which a particular species is either gaining or losing ground in an ecological system. Such changes may inform scientists and managers both in assessing current status of a forested system and in forecasting probable stand-scale shifts and changes in developmental patterns. Additionally, researchers have concluded that forest health problems can be identified and tracked through the investigation of shifts in species composition.

One way to determine shifts in species composition is through tracking species-specific relative stocking over time. Stocking is generally defined as the amount of growing space that a particular tree occupies in a given unit of land area (Avery and Burkhart 1994, Gansner and others 1996). Specifically, the USDA Forest Service Forest Inventory and Analysis (FIA) program defines stocking as "the degree of occupancy

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of land by trees, measured by basal area or the number of trees in a stand, compared with a minimum standard, depending on tree size, required to fully utilize the growth potential of the land." The FIA definition is based on the original stocking definition presented by Ginrich (1967).

This definition and FIA data were used to define changes of relative stocking values of common tree species in Kentucky from 1988 to 2004. Specific objectives of this investigation included extending the analysis begun by Gansner and others (1995), published in the proceedings of the 10th Central Hardwood Forest Conference, by 1) identifying and quantifying the strength and direction of shifts in relative stocking for common tree species in Kentucky from 1988-2004; 2) comparing current estimates of change with the previously reported estimates from Gansner and others (1995); and 3) identifying long-term and short-term trends in species-specific relative stocking changes.

DATA

Data used in this study were collected by the USDA Forest Service FIA program. Data were obtained from 1099 plots initially measured in 1986-1987 (hereafter 1988) according to FIA procedures for plots with a five-point cluster design with one center point and four satellite points located 98.4 ft north, east, south and west. The same plots were remeasured between 1999 and 2003 (hereafter 2004). The percent forest land in each county influenced the number of remeasured plots located in a given county. As a result, plots per county ranged from one for the counties containing limited forest land to 39 in one of the heavily forested counties (Table 1). The remeasured fixed area plot records allowed for the use of a consistent stocking estimation procedure to be applied to both inventories and comparisons to be made. In addition, estimates of species-specific change in relative stocking were obtained for the period between 1975-1988 from Gansner and others (1995) for comparisons with the estimates derived in the current analysis.

METHODS

Stocking

Species-specific stocking was calculated for both the 1988 and 2004 inventories with the following equation:

$$S_{iklj} = \frac{(b_0 \cdot dbh_{ikjl}^{b_1}) \cdot tpa_{ikjl}}{q_{ik}} \qquad (1)$$

where S_{iklj} = stocking value for tree *j* in condition *k* of subplot *l*, plot *i*; dbh_{iklj} = diameter at breast height of tree *j*, subplot *l*, condition *k* of plot *i*; tpa_{iklj} = trees per acre expansion factor of tree *j* on subplot *l*, condition *k* of plot *i*, reflecting the plot size disregarding condition; *qik* = stockability proportion for condition *k* of plot *i* (assumed to equal 1); and b_0 and b_1 = species-specific parameters. Species-specific coefficients were obtained from Tables 2 and 3 in Arner and others (2001).

Relative stocking was calculated for each species at the plot-level by:

$$RS_{hp} = \frac{\sum S_{hp}}{\sum S_{(all)p}} \qquad (2)$$

where, RS_{hp} is the relative stocking of species *h* on plot *p*; *S* is the calculated species-specific stocking; and $S_{(all)}p$ is the stocking calculated for all species on plot *p*.

Table 1.—Number of plots remeasured in 2004 and the percent forest land for each county in 2004 within the Commonwealth of Kentucky.

County	Plots	Forest (%)	County	Plots	Forest (%)
Adair	12	44	Larue	3	31
Allen	9	35	Laurel	16	58
Anderson	4	42	Lawrence	18	87
Ballard	5	24	Lee	10	81
Barren	5	19	Leslie	23	91
Bath	5	38	Letcher	20	91
Bell	19	85	Lewis	21	69
Boone	4	31	Lincoln	4	29
Bourbon	3	3	Livingston	10	40
Boyd	6	66	Logan	8	27
Boyle	2	38	Lyon	12	59
Bracken	4	46	Madison	4	27
Breathitt	25	92	Magoffin	24	84
Breckinridge	15	38	Marion	5	34
Bullitt	8	53	Marshall	7	37
Butler	11	53	Martin	15	76
Caldwell	8	28	Mason	7	23
Calloway	10	27	McCracken	9	21
Campbell	3	35	McCreary	11	87
Carlisle	4	28	McLean	2	17
Carroll	3	42	Meade	7	33
Carter	17	76	Menifee	10	77
Casey	13	54	Mercer	2	16
Christian	13	38	Metcalfe	8	36
Clark	2	22	Monroe	5	36
Clay	22	89	Montgomery	2	24
Clinton	6	49	Morgan	15	79
Crittenden	8	35	Muhlenberg	9	42
Cumberland	13	66	Nelson	8	36
Daviess	4	17	Nicholas	2	26
Edmonson	10	57	Ohio	17	48
Elliott	10	71	Oldham	2	22
Estill	10	80	Owen	9	42
Fayette	2	1	Owsley	9	78
Fleming	8	41	Pendleton	7	45
Floyd	19	84	Perry	19	80
Franklin	3	26	Pike	39	84
Fulton	4	18	Powell	8	73
Gallatin	1	37	Pulaski	16	48
Garrard	2	23	Robertson	2	56
Grant	4	37	Rockcastle	14	67
Graves	11	22	Rowan	13	73
Grayson	13	41	Russell	6	40

continued

Table 1.—Number

Green	4	24	Scott	3	21
Greenup	15	75	Shelby	4	19
Hancock	4	50	Simpson	2	6
Hardin	14	31	Spencer	3	35
Harlan	26	92	Taylor	6	36
Harrison	4	18	Todd	6	26
Hart	9	46	Trigg	20	54
Henderson	3	10	Trimble	4	48
Henry	3	30	Union	3	13
Hickman	3	25	Warren	7	24
Hopkins	11	40	Washington	3	27
Jackson	14	78	Wayne	18	72
Jefferson	1	17	Webster	5	29
Jessamine	2	18	Whitley	21	72
Johnson	13	77	Wolfe	11	82
Kenton	3	40	Woodford	3	3
Knott	17	90			
Knox	16	77	Total	1099	

Estimating Change

Change was estimated by comparing species-specific relative stocking for a given plot across both inventories by:

$$SC_{hp} = RS_{1988} - RS_{2004} \qquad (3)$$

where SC_{hp} is stocking change for species *h* on plot *p*.

Average annual change (AAC) was calculated for each species at the plot scale:

$$AAC_{hp} = \frac{SC_{hp}}{RP} \qquad (4)$$

where RP is the time between remeasurements of the plot.

Mean species-specific average annual change AAC_{hp} was calculated for each county in Kentucky. Average annual change calculated for the period between 1988 and 2004 was compared to estimates of average annual change between period 1975 and 1988 reported by Gansner and others (1995). Direction (positive or negative AAC_{hp}) for both periods were compared to detect possible long-term trends in species composition. In addition, change (positive, negative, and no change) was mapped for select species to detect spatial trends in changes.

Table 2—Stocking equation coefficients for each species and number of plots in which a species was postively identified at Time 1 (1988) and Time 2 (2004)

	--------Coefficients --------				
Species	b0	b1	Time1	Time2	Difference
Red maple	0.01105	1.53	306	440	134
Eastern redcedar	0.00946	1.59	108	175	67
Sugar maple	0.00694	1.86	295	358	63
Shortleaf pine	0.00509	1.81	41	73	32
Pitch pine	0.00946	1.59	41	69	28
Boxelder	0.00688	1.86	33	56	23
Yellow buckeye	0.00694	1.86	17	37	20
Shumard oak	0.01119	1.63	5	24	19
Eastern hemlock	0.00313	2.11	27	42	15
Eastern white pine	0.009	1.51	8	15	7
Ailanthus	0.01105	1.53	2	6	4
Balsam poplar	0.01429	1.46	0	3	3
Swamp white oak	0.01119	1.63	3	6	3
Bur oak	0.0025	2	0	1	1
Loblolly pine	0.0068	1.72	8	8	0
Striped maple	0.00694	1.86	1	1	0
American chestnut	0.01105	1.53	1	0	-1
Silver maple	0.01105	1.53	17	16	-1
Osage orange	0.01119	1.63	12	10	-2
Overcup oak	0.01119	1.63	2	0	-2
Cherrybark oak	0.01119	1.63	23	19	-4
Pin cherry	0.01105	1.53	4	0	-4
Eastern cottonwood	0.00688	1.86	11	6	-5
Willow spp.	0.01105	1.53	17	8	-9
Pin oak	0.01119	1.63	23	13	-10
Blackjack oak	0.01119	1.63	15	2	-13
River birch	0.00635	1.89	28	14	-14
Shingle oak	0.01119	1.63	28	13	-15
Post oak	0.01119	1.63	104	76	-28
American sycamore	0.00688	1.86	112	76	-36
American beech	0.00694	1.86	246	199	-47
Scarlet oak	0.01119	1.63	227	161	-66
Chestnut oak	0.01119	1.63	303	235	-68
White oak	0.01119	1.63	527	419	-108
Northern red oak	0.01119	1.63	352	225	-127
Black oak	0.01119	1.63	431	278	-153

RESULTS

In 1988 white oak (*Quercus alba*) occurred on the most plots (527 plots) followed by yellow-poplar (*Liriodendron tulipifera* L.) (448 plots), black oak (*Q. velutina* Lam.)(431 plots), northern red oak (*Q. rubra* L.) (352 plots) and red maple (*Acer rubrum* L.) (306 plots). After remeasurement in 2004, red maple was sampled on the most plots (440 plots) followed by white oak (419 plots), yellow-poplar (383 plots), sugar maple (*A. sacharrum* Marsh.) (358 plots) and black oak (278 plots).

Between 1988 and 2004 the presence of red maple, eastern redcedar, and sugar maple increased significantly (Table 2). Other species that increased in presence were shortleaf (*Pinus echinata* P. Mill.) and pitch pines (*P. rigida* P.Mill.), boxelder (*Acer negundo* L.), eastern hemlock (*Tsuga Canadensis* (L.) Carr.), and eastern white pine (*P. strobus* L.). Species from the oak (*Quercus*) genus had the greatest declines in presence. Five species of oak in particular—black oak, northern red oak, white oak, chestnut oak (*Q. prinus* L.), and scarlet oak (*Q. coccinea* Muenchh.)—were found on approximately 50 fewer plots in 2004 than in 1988 (Table 2). In addition, six other oak species, post oak (*Q. stellata* Wangenh.), shingle oak (*Q. imbricaria* Michx.), blackjack oak (*Q. marilandica* Muenchh.), pin oak (*Q. palustris* Muenchh.), cherrybark oak (*Q. pagoda* Raf.), and overcup oak (*Q. lyrata* Walt.) were identified on significantly fewer plots in 2004 than in 1988.

The 18 species with the largest positive AAC and 18 species with the largest negative AAC between 1988 and 2004 are presented in Figure 1. Species such as eastern white pine, boxelder, and loblolly pine experienced gains in relative stocking of greater than 1 percent year-1. Only eastern cottonwood experienced loses of greater than 1 percent year^{-1}. Oaks averaged losses of 0.02 percent year^{-1}, while maples averaged gains of approximately 0.11 percent year^{-1}. The six most common oaks averaged losses of 0.29 percent year^{-1}. Oaks represented 61 percent of the top 18 species that decreased in abundance.

The relative stocking of 11 species of oak decreased between 1988 and 2004 (Fig. 1). Other species that had significant declines in relative stocking were river birch (*Betula nigra* L.), American sycamore (*Platanus occidentalis* L.), pin cherry (*Prunus pennsylvanica* L.f., and willow (*Salix* spp. L.).

Two genera, *Pinus* (pines) and *Acer* (maples), represented a large proportion of the species that gained in relative stocking between 1988 and 2004. Significant gains were recorded for five maple species and four pine species. The maples were found on many more plots than the pines (Table 2). Red maple, sugar maple, boxelder, striped maple, and silver maple were sampled on 440, 358, 56, 1, and 16 plots, respectively in 2004. While silver maple was recorded on one fewer plot (Table 2) in 2004 than 1988 it exhibited a positive AAC. Shortleaf pine, pitch pine, eastern white pine and loblolly pine were recorded on 73, 69, 15, and 8 plots, respectively in 2004. Other species with significant positive AAC were eastern redcedar (*Juniperus virginiana* L.), balsam poplar (*Populus balsamifera* L.) and the invasive tree-of-heaven (*Ailanthus altissima* (P.Mill.) Swingle).

Arguably the most important analysis is the long-term (1975 to 2004) change in species-specific relative stocking. When compared to similar estimates of AAC for the period between 1975 and 1988, 11 species were found to be experiencing a long-term decline in relative stocking over the combined 30-year period between 1975 and 2004 (Fig. 2). Ten species experienced gains in relative stocking over the same period while 14 species were found to be increasing during one study (1975-1988 or 1988-2004) and decreasing during the other (short-term)(Fig. 2). Long-term declines in relative stocking have been experienced by

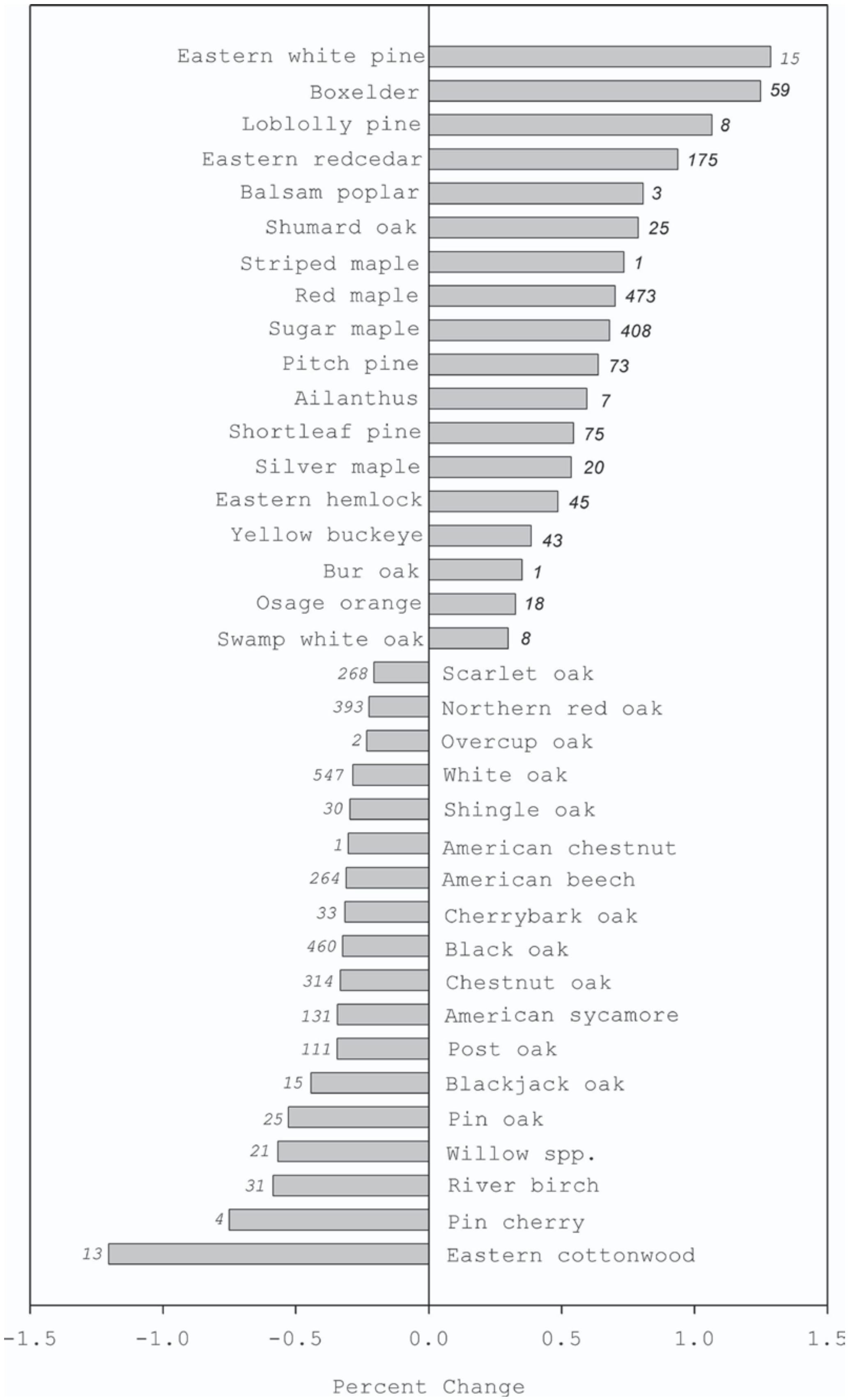

Figure 1.—Average annual change in relative stocking (percent change year^{-1}) of the 18 largest increasing and decreasing forest tree species in Kentucky from 1988-2004. Number of independent plots used in the analysis are in parentheses.

five species of oak, while long-term increases in relative stocking were calculated for four maple species. Species such as pitch, Virginia, and shortleaf pine exhibited short-term increases (Fig. 2). In contrast, species such as white oak, chestnut oak, southern red oak, sassafras (*Sassafras albidum* (Nutt.) Nees), and yellow-poplar have experienced short-term declines in relative stocking.

Species	1975 - 1988	1988 - 2004
American beech	↓	↓
Scarlet oak		
Northern red oak		
Post oak		
Black oak		
Black walnut		
Chinkapin oak		
Dogwood		
Eastern redbud		
Elm spp.		
Sweetgum		
Pitch pine	↓	↑
Black locust		
Blackgum		
Hackberry		
Hickory spp.		
Shortleaf pine		
Virginia pine		
Sycamore	↑	↓
White oak		
Chestnut oak		
American basswood		
Sassafras		
Southern red oak		
Yellow poplar		
Eastern redcedar	↑	↑
Boxelder		
Red maple		
Silver maple		
Sugar maple		
Yellow buckeye		
Black cherry		
Green ash		
Sourwood		
White ash		

Figure 2.—Direction of average annual change in relative stocking of some common forest tree species for the periods of 1975-1988 and 1988-2004 in Kentucky.

DISCUSSION

The results support the generally accepted notion that the eastern deciduous landscape continues to experience oak replacement by more generalist species such as red maple. Of the tree species that experienced gains in relative stocking between 1988 and 2004, five of the top 13 species that increased in relative stocking were of the *Acer* genus. Three of the five were recorded in considerably more plots in 1988 than in 2004, particularly red maple. Concomitantly, the stocking of numerous oak species decreased across the state. Eleven of the 18 species that declined the greatest in relative stocking were oak species. Five of the oak species (black, northern red, white, chestnut, and scarlet) were observed on 50+ fewer plots in 2004 than in 1988. White oak, northern red oak, and black oak were observed on 100+ fewer plots, indicating significant and widespread decreases in the stocking of numerous oak species.

These trends were reported 10 years ago by Gansner and others (1996). Maples continue to gain while oaks lose ground with respect to relative stocking. The most common species of oak are decreasing in relative stocking at a pace of approximately 0.29 percent year^{-1} and the maples are gaining ground at a pace of 0.11 percent year^{-1}. These rates indicate that some of the most common oak species are being replaced by maples and other species. In fact, a few oak species (bur (*Q. macrocarpa* Michx.), Shumard (*Q. shumardii* Buckl.), and swamp white (*Q. bicolor* Willd.)) had observed gains between 1988 and 2004 along with multiple pine species, eastern hemlock, and the invasive tree-of-heaven.

While some species appeared to have large gains or losses in stocking, (e.g., eastern cottonwood, eastern white pine and loblolly pine) the relatively low number of plots that the species was recorded on must be accounted for and could inflate AAC values. However, the importance of information regarding relatively rare species within a given geographic area is considerable. That is, it is extremely important to know when the presence of a species within a given area drops below the ability for a particular inventory to capture it. For example, in the remeasured plots used in this study American chestnut (*Castanea dentata* (Marsh.) Borkh.) was recorded on one plot in 1988 and not recorded in 2004. On the other hand, while the invasive tree-of-heaven was found on only six plots in 2004 it was recorded on only two plots in 1988, an increase of 200 percent. The implication is that data from large-scale inventories can be used not only to recognize when a species becomes incredibly rare, but also to track increased stocking of nonnative invasive trees.

CONCLUSION

It appears that many early succesional species and advance reproduction-dependent intermediate shade-tolerant species are declining in relative stocking. Concomitantly, many shade-tolerant species and advance reproduction-independent species continue to increase in relative stocking, suggesting general changes in disturbance patterns and an aging forest resource.

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FORTY-TWO YEARS OF CHANGE IN AN OLD-GROWTH AND SECOND-GROWTH BEECH-MAPLE FOREST OF NORTH CENTRAL OHIO

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Abstract.—Using data collected in 1964 and 2006, we examined changes in the composition and structure of a second-growth and old-growth beech-maple forest of Crall Woods, located in Ashland County of north central Ohio. Over the 42 years, the old-growth forest (estimated to be at least 250 years old) experienced a significant shift in species composition as American beech, yellow-poplar, and red maple increased in importance while American basswood, sugar maple, and shagbark hickory all declined in importance. Similar changes were observed in the second-growth stand, except that the increases in importance were associated with shade-intolerant (e.g., yellow-poplar) and shade mid-tolerant (e.g., northern red oak) species. Despite the shifts in composition, stand structure remained fairly consistent over the 42 years and was similar between the second-growth and old-growth stand. We suggest that the old-growth stand will continue to have both shade-tolerant and intolerant species over time and that the composition of the second-growth stand will shift toward the more shade-tolerant species. These species will dominate the forest understory as they replace shade-intolerant and mid-tolerant overstory individuals that die.

INTRODUCTION

Of the original 140 million hectares of forests that once dominated the Central Hardwood Region, only 0.07 percent (100,000 hectares) remains as old-growth (Parker 1989). Since old-growth stands are often the least disturbed portions of current landscapes, they are often used as a baseline, or reference system, to plan and evaluate forest restoration projects (Stephenson 1999, Moore and others 1999, Goebel and others 2005). Additionally, a better understanding of how mature forest ecosystems change over time will help us understand and predict how disturbances will influence forests in the future (Goebel and others 2005), which ultimately will lead to better management techniques for younger, second-growth forests (Barnes 1989, Parker 1989, Acker and others 1998, Martin and Bailey 1999). However, to develop more ecologically-based management systems that emulate the outcomes of natural disturbance (i.e., ecological forestry as defined by Mitchell and others 2006), more information on the natural successional pathways is needed, particularly if we wish to understand how these natural shifts in composition and structure occur over time or wish to guide the successional pathways of younger stands.

A large portion of the Central Hardwood forest in Ohio is within the till plains, a physiographic region with low relief and minor changes in elevation (Braun 1956, McNab and Avers 1994, Dolan and Parker 2005). Across this region, beech-maple (*Fagus-Acer*) forests are characterized by species including American beech (*Fagus grandifolia* Ehrh.) and sugar maple (*Acer saccharum* Marsh.), and to lesser degree white ash (*Fraxinus americana* L.) and yellow-poplar (*Liriodendron tulipifera* L.). These beech-maple forests also historically occupied till plains in surrounding states, such as Indiana, Pennsylvania, and Michigan, as

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well as in Canada (Braun 1956). Although fire may have historically played a role in shaping these forests, in recent decades disturbances to these beech-maple forests have been primarily limited to canopy gaps caused by the death of one or a few trees. The rate at which canopy gaps are formed in eastern mesic forests averages 1 percent yr^{-1}, resulting in a natural stand turnover time of approximately 100 years (Runkle 1982). Unfortunately, very few old-growth beech-maple forests remain; those stands that do exist were preserved mainly because the land on which they are situated was unsuitable for agriculture (Braun 1956, Parker 1989).

Although many studies have examined how old-growth forests in the Central Hardwood Region change over time, most of these have examined the current composition and structure of old-growth mixed-oak (*Quercus*) forests, mixed-mesophytic forests, or mixed coniferous and hardwood stands (e.g., Whitney 1984, Martin and Bailey 1999, McCarthy and others 2000, Galbraith and Martin 2005). Studies conducted in old-growth beech-maple forests in the region are less numerous, but have included examining the environmental factors that define beech-maple forests (Whitney 1982), the changes in seedling composition in gaps over time (Kupfer and Runkle 1996), short-term changes in overstory and understory composition (Foré et. al. 1997), gap dynamics and their subsequent effects on the herb layer (Moore and Vankat 1986), mortality and replacement patterns of the overstory (Forrester and Runkle 2000) and of the understory (Boerner and Brinkman 1996), and present stand composition and structure (Cain 1935, Pell and Mack 1977). However, few studies have actually examined the changes in composition and structure in the overstory and/or understory of old-growth beech-maple stands of the Central Hardwood Region (Abrell and Jackson 1977, Foré and others 1997, Forrester and Runkle 2000).

One study of an old-growth, beech-maple forest in the Central Hardwood Region that is often overlooked was conducted in 1964 by John Aughanbaugh, a silviculturist with the Ohio Agricultural Experiment Station (Aughanbaugh 1964). In this report, Aughanbaugh described the composition and structure of an old-growth and an adjacent second-growth beech-maple stand at Crall Woods. The objective of our study was to resample these stands at Crall Woods, and examine the changes in composition and structure over a period of 42 years. Specifically, we wished to determine: 1) if the composition and structure of the old-growth stand was relatively stable, and 2) if there has been a shift in composition and structure in the second-growth stand so that it more closely resembles the old-growth stand at Crall Woods.

STUDY AREA

Crall Woods is a 37.4-ha tract located in north central Ohio in Ashland County. In 1974, the National Park Service registered Crall Woods as a National Natural Landmark, one of only 587 registered sites in the United States and one of only 23 sites in Ohio. Crall Woods is located within the central till plains physiographic region (Dolan and Parker 2005), in the beech-maple forest region as determined by Braun (1956). The area is characterized by gently rolling topography, and ranges from 200 to 300 m in elevation (McNab and Avers 1994). The predominant soil series of the area is Bennington silt loam, which is a poorly drained Alfisol originating from glacial till (Aughanbaugh 1964). Precipitation averages 900 to 1,030 mm a year and annual temperatures range from 10 to 13 °C (McNab and Avers 1994).

There are four distinct forest stands at Crall Woods: a 17.8-ha eastern red cedar (*Juniperus virginiana* L.) stand along the southernmost point of the forest; a 20.2-ha young mixed-hardwood stand at the northern end of the forest; a 4.0-ha mature second-growth stand south of the young mixed hardwood stand dominated by oaks and maples; and a 16.18-ha old-growth beech-maple stand. Recent human influence on the old-growth stand appears to have been minimal as no cut stumps were found. Also, there is little indication of livestock grazing as evidenced by the remnants of an old fence separating the old-growth stand from other areas of Crall Woods and by the diverse spring and summer ground-flora.

Our study focused on both the mature second-growth and the old-growth stand. Increment cores show that the second-growth stand is between 130 and 140 years old and the old-growth stand is 200-250 years old. We speculate that the old-growth and second-growth stands most likely originated in the 1700s after some form of major stand-replacing disturbance. About 100 years later, around the time of European settlement, the second-growth stand was most likely harvested. For the past 140 years, both stands appear to have been allowed to develop with minimal human interference. During sampling, Crall Woods appeared to be unusually wet compared to the surrounding landscape, implying it was probably not as suitable for agriculture. Subsequent to 1981, a tornado damaged part of the old-growth stand, although it is unclear which part (Davis 1993). Presently, however, the most likely types of disturbance affecting both the second-growth and old-growth stands are canopy disturbances caused by natural tree mortality, and blowdowns caused by the wind.

METHODS

Data Collection

In 1964, John Aughanbaugh conducted a complete inventory of Crall Woods (Aughanbaugh 1964). He inventoried all stems >30 cm in the old-growth stand and all stems >5 cm in the second-growth stand. Measurements included the diameter at breast height (d.b.h) and species for each stem, as well as the volume of standing timber by species.

In 2006, we randomly established nine 2500-m² plots in Crall Woods with seven plots in the old-growth stand and two plots in the mature second-growth stand. We recorded species and d.b.h. of all trees >10 cm d.b.h. For comparisons of stand conditions between 1964 and 2006, we included only the range of tree diameters measured on both occasions: trees >30 cm for the old growth stand and trees >10 cm for the second-growth stand.

Data Analysis

Relative densities and relative basal areas for all species were calculated for both the old-growth and second-growth stands in 1964 and in 2006. Additionally, we calculated an importance value (calculated as the sum of relative basal area and relative density divided by 2) for each species. Basal area calculations for the 1964 data were limited as Aughanbaugh (1964) provided only abundance of individuals by species in each 5-cm d.b.h. class (>30.0 cm in old-growth stand and >5.0 cm in second-growth stand). Therefore, basal areas were estimated by d.b.h. class for these data using the midpoint of each d.b.h. class.

RESULTS

Changes in the Old-Growth Stand

In 1964, the old-growth stand was dominated by sugar maple, American basswood (*Tilia Americana* L.), American beech, shagbark hickory (*Carya ovata* (P. Mill.) K. Koch), American elm (*Ulmus americana* L.), and white ash, while in 2006 the stand was dominated by sugar maple, American beech, yellow-poplar, and American basswood (Table 1). In terms of importance values, the most significant changes included a 20.3 percent and 8.6 percent increase in American beech and yellow-poplar, respectively. Decreases in importance included an 8.9 percent, 8.8 percent, 6.3 percent, and 4.4 percent decline in American basswood, sugar maple, shagbark hickory, and American elm, respectively (Fig. 1).

Table 1.—Species' importance values and changes over the 42-year period for the old-growth stand and for the second-growth stand at Crall Woods

	Importance Value					
	Second-growth			Old-growth		
Species	1964	2006	Percent change	1964	2006	Percent change
Fagus grandifolia	7.27	8.77	1.50	12.94	33.28	20.34
Liriodendron tulipifera	0.47	0.93	0.46	4.76	13.35	8.58
Acer rubrum	0.00	4.04	4.04	1.14	3.25	2.12
Carya glabra	1.69	3.26	1.56	1.25	2.09	0.84
Prunus serotina	5.04	2.30	-2.75	0.09	0.32	0.22
Fraxinus americana	13.60	20.23	6.64	5.42	5.46	0.04
Ostrya virginiana	3.19	0.47	-2.72	0.00	0.00	0.00
Juglans nigra	5.34	0.00	-5.34	0.37	0.32	-0.05
Quercus alba	0.59	0.49	-0.10	.012	0.00	-0.12
Quercus rubra	15.27	22.39	7.11	2.03	0.00	-2.03
Ulmus americana	3.29	0.54	-2.75	5.47	1.07	-4.40
Carya ovata	9.04	4.47	-4.57	6.62	0.37	-6.26
Acer saccharum	5.79	14.36	8.57	36.92	28.10	-8.82
Tilia americana	26.87	17.77	-9.10	21.25	12.40	-8.85

Although significant shifts in species composition were detected over the 42-year period, few changes were observed in stand structure. Stem density (stems·ha^{-1}) remained consistent at 123 stems·ha^{-1}. Basal area values increased slightly from 25.1 m^2·ha^{-1} in 1964 to 27.9 ± 2.99 m^2·ha^{-1} in 2006.

Changes in the Second-Growth Stand

Species composition, as indicated by species importance values, remained more consistent in the second-growth stand over the 42 years compared with the old-growth stand. In 1964, the second-growth stand was dominated by six species: American basswood, northern red oak (*Q. rubra*), white ash, American beech, shagbark hickory, and sugar maple. In 2006, the stand was dominated by the same species with a reduction in shagbark hickory and an increase in American beech (Table 1). There were major shifts in importance values: an 8.6 percent increase for sugar maple, a 7.1 percent increase for northern red oak (Fig. 1), a 6.6 percent increase for white ash, and a 4.0 percent increase for red maple. There was a 9.1 percent decrease for American basswood and a 4.6 percent decrease for shagbark hickory.

In terms of stand structure, stem densities decreased sharply from 685 stems·ha^{-1} in 1964 to 394.0 stems·ha^{-1} in 2006. Total basal area over the 42 year period in the second-growth stand increased slightly from 41.2 m^2·ha^{-1} to 43.0 ± 3.48 m^2·ha^{-1}, values that are higher than those observed in the old-growth stand.

DISCUSSION

In forest ecosystems lacking frequent, large-scale disturbances, changes in species composition and structure are caused mainly by competition among individual trees for space and resources (Oliver and Larson 1996). By determining the changes in composition and structure that are experienced, we can draw a more detailed picture of forest succession that is specific to forest type. We can identify the successional pathways of old-growth forests as well as those of forests that have disturbed more recently.

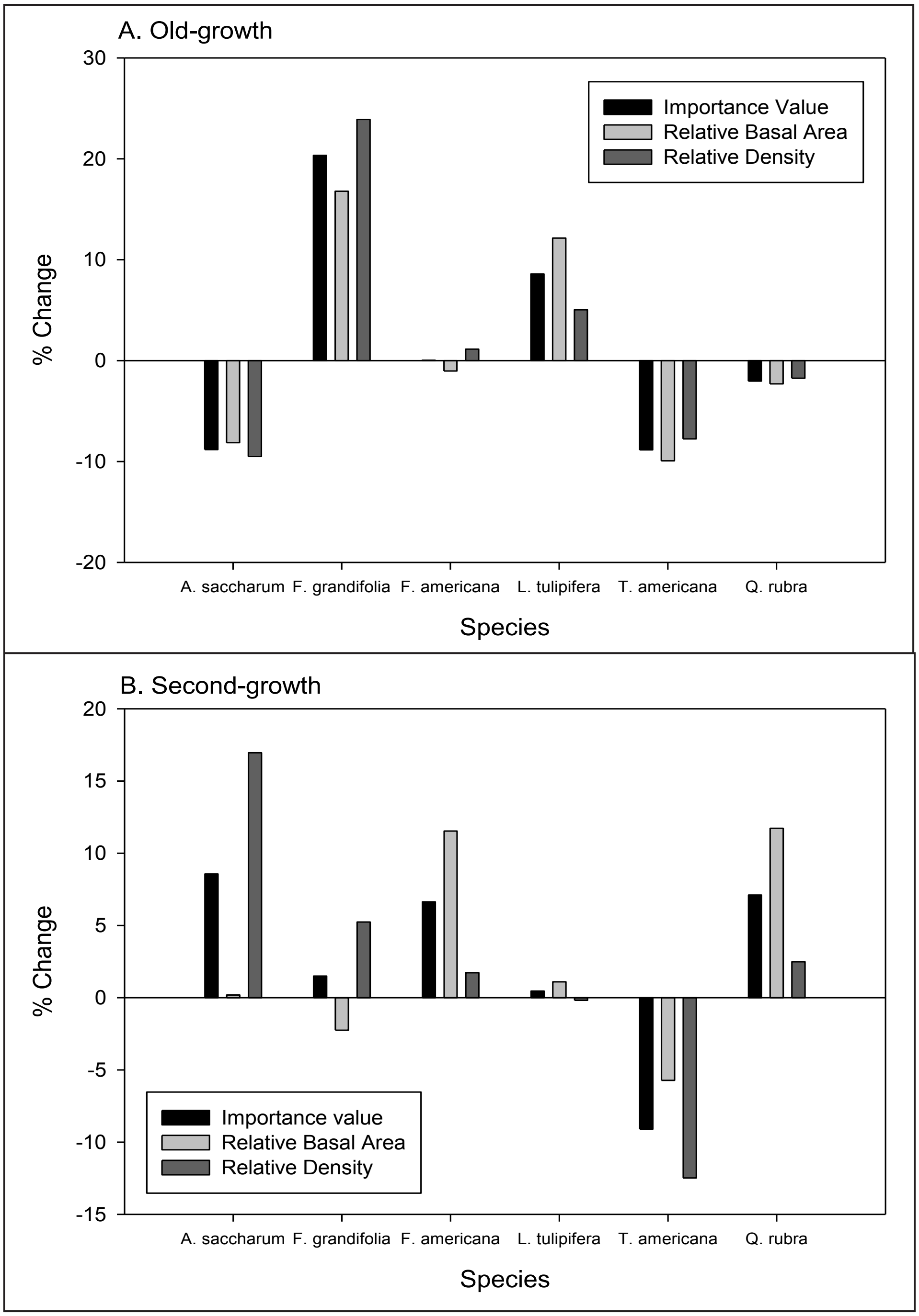

Figure 1.—Percent change in importance value, relative density, and relative basal area for selected species from 1964-2006 in the old-growth stand (A) and second-growth stand (B) at Crall Woods, Ashland County, Ohio.

During the 42-year period at Crall Woods, we observed minimal changes in the overall species composition of the old-growth stand. The two most important species (sugar maple and American beech) remained dominant over the 42-year period. Some shade mid-tolerants also increased in importance. The magnitude of change is typical of changes that occur in old-growth forests (Oliver and Larson 1996), with both shade-tolerant species and shade-intolerant species increasing in abundance in small gaps and later successional species (shade tolerants in closed canopy forests) remaining dominant in the overstory and understory. These shifts in species composition vary in their consistency compared with other studies examining the changes in beech-maple, old-growth forest species composition over time. For instance, an old-growth beech-maple forest at the Holden Arboretum in northeastern Ohio experienced a 1.2 percent increase in the importance value of sugar maple and a 0.9 percent decrease in the importance of American beech over a period of 5 to 6 years (Forrester and Runkle 2000). Hueston Woods, an old-growth beech-maple forest in southwestern Ohio, also experienced minimal changes over a 7-year period (Foré and others 1997). The importance of sugar maple did not change and there was only a slight reduction (1.9 percent) in the importance of American beech. The importance of other species remained relatively constant (<1 percent changes) whereas the old-growth stand at Crall Woods experienced larger shifts in species composition over time. However, this difference may be related to the longer length of time between sample periods (i.e., 7 years versus 42 years).

There are examples of significant shifts in species composition in old-growth beech-maple forests. In Indiana, an old-growth beech-maple forest experienced a 10 percent increase in importance value of sugar maple and a 7.2 percent reduction in importance value of American beech over a 10-year period (Abrell and Jackson 1977), which are different from our results (i.e., we experienced a decrease in sugar maple and an increase in American beech). The stand also experienced an increase of 4.3 percent in the importance value of yellow-poplar, which is consistent with our findings. Abrell and Jackson (1977) report minimal changes in stand structure despite these shifts in species composition. Runkle (2000) conducted studies on compositional changes in old-growth stands in Ohio, Pennsylvania, Tennessee, and North Carolina. He also summarized changes in several old-growth stands in the region and found that American beech decreased in importance over most of its geographic range and that sugar maple increased. Runkle also found that, similar to our study, minimal changes in stand density and basal area in the old-growth stands occurred.

In the second-growth stand, over the last 42 years, the continued importance of both northern red oak and yellow-poplar, which are considered intolerant to mid-tolerant of shade (Burns and Honkala 1990), are most likely a result of the longevity of the species. We would not expect them to be able to maintain this strong presence as the mature individuals die and those regenerating are mostly outcompeted by more shade-tolerant species, such as sugar maple and American beech. The second-growth stand is still in the understory reinitiation stage (*sensu* Oliver and Larson 1996), in which understory individuals are ascending into the canopy and shade-tolerant individuals have not yet begun to dominate the overstory. The course of change in the second-growth stand, from shade intolerants and mid-tolerants to shade tolerants, has been documented in other studies in the Central Hardwood Region (Piussi 1966, Whitney 1984, Dodge 1997, Galbraith and Martin 2005). As the second-growth stand develops over time, we expect that it will more closely resemble the old-growth stand in terms of species composition, with an increase in importance of both sugar maple and American beech. However, we would anticipate that the structure of the stands will remain much the same as other studies have shown few differences in stem density and basal area between adjacent old-growth and second-growth stands of the same type (Angers and others 2005, Foré and others 1997, Forrester and Runkle 2000).

This study has shown that in the Central Hardwood Region, when younger stands containing shade-intolerant species are left unmanaged, their composition will shift, over time, to a species composition of more shade-tolerant individuals (in the absence of fire and other large disturbances). As a result, active management of these stands (e.g., thinning, herbicide treatment, and prescribed burning) is required if mid-tolerant or intolerant species composition is desired. Additionally, this study has provided one example of the time required for a recently cleared stand that is subsequently not managed, to attain the characteristics of an old-growth stand, in this case, about 150 years.

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CURRENT FOREST CONDITIONS OF OLDER STANDS OF THE MIXED MESOPHYTIC FOREST REGION ON THE APPALACHIAN PLATEAUS PROVINCE OF EASTERN KENTUCKY

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Abstract.—E. Lucy Braun coined the term "mixed mesophytic forest" in 1916. These forests are structurally complex and occur extensively across the Appalachian Plateaus Province. This region is considered the epicenter of highest development of the eastern deciduous forest. I used U.S. Forest Service, Forest Inventory and Analysis (FIA) data to study current forest conditions of this mixed mesophytic region on the Cumberland and Allegheny Plateaus in eastern Kentucky. A study population made up of 186 FIA plots with a quadratic mean diameter ≥30 cm, was used in the analysis. Across eastern Kentucky, these types of stands averaged 23.9 m^2 ha^{-1} in basal area and 277 stems ha^{-1} in the overstory. The McIntosh Evenness Index was used to quantify the degree of stand dominance, where 1.0 equaled an even representation of all species present on the plot. These 186 plots had an average evenness index of 0.84, indicating an expectedly high degree of species evenness in these structurally complex stands. Based on the dominant species, 10 forest communities were recognized. The most common community was *Quercus prinus*, occurring on 39 plots; second was the *Fagus grandifolia* community (29 plots), third was *Liriodendron tulipifera* (27 plots), and fourth was *Q. alba* (26 plots). Overstory species richness averaged 7.4 species per plot. The study, using a probability-based large-scale sample design, describes forest conditions across the Appalachian Plateaus Province in Kentucky. Defining FIA plots that represent stands that are mature associations of Braun's mixed mesophytic forest poses problems because these stands are in various stages of recovery and succession from past disturbance.

INTRODUCTION

The Appalachian Plateaus Province of eastern Kentucky is considered to be the center of highest development of the eastern deciduous forest (Braun 1950). This area lies just west of the Appalachian Mountains and here the total environmental complex favors maximum complexity of forest development (Smith 1995). The forests of the mixed mesophytic forest region have been heavily disturbed over the last 100 years. Very few remnants of virgin forest remain (Quarterman and Turner 1972, Martin 1975, Muller 1982, McCarthy and others 1987, Braun 1950).

Braun labeled the complex forests of this region the "mixed mesophytic forest" because of the high degree of structural complexity and multitude of possible species combinations (Braun 1916). Her naming convention considered this as an association, a major climax unit of the formation. Examples of formations are the deciduous forest and the grassland. Examples of associations are mixed mesophytic and oak-hickory. The multitude of different forest communities in the mixed mesophytic forest association were defined as association-segregates (Braun 1950). Examples are beech-maple and white oak-red maple. Although Braun included all of the Cumberland and the unglaciated Allegheny Plateau of eastern Kentucky in the mixed mesophytic forest region she noted that the best development of these forests was in ravines, gorges,

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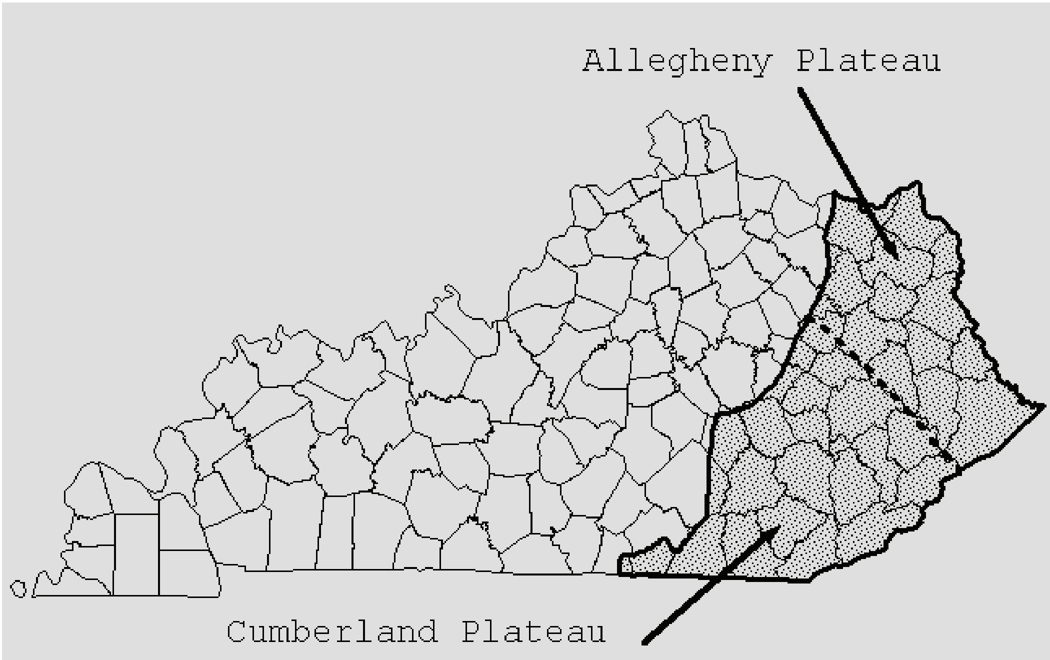

Figure 1.—The Appalachian Plateaus Province in eastern Kentucky with the unglaciated Allegheny Plateau Section in the north and the Cumberland Plateau Section in the south. After Fenneman (1938).

coves, and valleys on the Plateau where topography was mature enough to support the mesic species (Braun 1950). This observation suggests that she thought the mixed mesophytic variants would be more widespread across the plateau once the erosion cycle was complete.

Braun studied the eastern deciduous forests in the first half of the 20th century with many of her study sites located in eastern Kentucky. One of her goals was to study and document the complexity of the virgin remnants before all were lost to logging. The culmination of this work was the highly acclaimed treatise "Deciduous Forests of Eastern North America" (Braun 1950).

With most of the forests in eastern Kentucky in various stages of recovery from past disturbance, it is unknown what the current conditions are and how much older forest remains. Braun used preferential sampling to selectively choose sites for study. My approach was to use a post-stratified selection of plots from a landscape-level systematic sampling scheme and to use stand size as a surrogate for age. The purpose of the study was to describe the current composition and structure of older stands on the Appalachian Plateaus Province of eastern Kentucky.

METHODS

The study area is the Appalachian Plateaus Province of eastern Kentucky (Fig. 1). The study area contains 30,327 km^2 , of which 23,405 km^2 are forested. Included in this physiographic province is the Cumberland Plateau to the south, the unglaciated Allegheny Plateau to the north, and a small portion of the Cumberland Mountains in the southeast. The boundary between the Cumberland Plateau and the unglaciated Allegheny Plateau runs northwest to southeast and is mostly indeterminate (Fig. 1). The difference between the two is based upon the degree of topographic dissection (Fenneman 1938). The study population includes plots on forest land across 36 eastern Kentucky counties.

The data came from the U.S. Forest Service, Forest Inventory and Analysis (FIA) program. The plot placement is systematic, where one sample plot is located inside each hexagon of a hexagonal grid superimposed across the State. Each hexagon encompasses approximately 2,430 ha.

Across the state of Kentucky were 6,116 sample plots (sample units), measured between 1999 and 2005. I used GIS software to select 1,227 sample units in the hexagonal grid that fell within the Appalachian Plateaus Province boundary. Each plot consisted of a cluster of four circular 0.017-ha subplots (7.3 m radius); total sample unit area was 0.068 ha. Subplot 1 was the center of the cluster with the three remaining subplot centers located 36.6 m away at azimuths of 360°(subplot 2), 120°(subplot 3), and 240°(subplot 4). A perimeter circle that encloses the outer boundaries of the subplots' sample unit footprint is approximately 0.60 ha.

All trees with a diameter at breast height ≥12.7 cm (d.b.h.) were measured on each subplot. Nomenclature follows Little (1979). To satisfy elements of the study, I selected only plots that had a quadratic mean diameter (q.m.d.) (Avery and Burkhart 1994) ≥30.0 cm and that had homogeneous forest conditions across all four subplots. The homogeneity issue is important because the FIA program utilizes a sampling scheme that involves mapping and partitioning different forest and nonforest conditions across plots. This procedure could result in unequal-sized plots and unusually high variances, elements which weaken rigorous analysis (Bechtold and Scott 2005, Husch and others 1982). Eliminating plots with mapped situations or plots with a q.m.d. <30.0 cm left 186 plots for the study population.

Forest community identification and nomenclature was based upon the No. 1 ranked species, by basal area, on each plot. Species richness was the number of tree species ≥12.7 cm in d.b.h. on each plot. The McIntosh Index (McIntosh 1967) was used to assess the degree of species evenness on each plot, where 1.00 is perfect evenness and where numbers approaching 0.00 indicate less even representation of all species present, i.e., a large proportion of the dominance in one or two species (Pielou 1977, Causton 1988, Magurran 1988).

RESULTS

There were 3,480 trees ≥12.7 cm d.b.h. measured on the 186 study plots. Fifty-six tree species occurred across these plots (Table 1). Across all plots, basal area averaged 23.9 m^2 ha^{-1}; density averaged 277 trees ha^{-1}. Average species richness was 7.4 species per plot and the species evenness index was 0.84.

Site characteristics were documented by aspect and slope on each plot. Aspect was grouped into five classes (Lloyd and Lemmon 1970): (1) northeast facing; (2) north and east; (3) northwest and southeast; (4) west and south; and (5) southwest. These aspects are ranked from most favorable (northeast facing) for tree growth to least favorable (southwest). The aspect classes are uneven in size because they are grouped on the basis of productivity, so the northeast class does not cover as many degrees of aspect as the second best class, which covers the north and east aspects. Most of the FIA plots fell on the north and east class (60 plots). Sizable numbers were located on the northwest and southeast class, and the west and south class, 44 and 42 plots respectively (Table 2). Basal area, density, and species richness were lowest on the west- and south-facing class.

Table 1.—Basal area and density of individual tree species on the Appalachian Plateaus Province of eastern Kentucky, n = 186

Species	Basal Area	Density
	m^2 ha^{-1}	stems ha^{-1}
Pinus echinata Mill.	0.1	1.3
Pinus rigida Mill.	0.1	0.6
Pinus strobus L.	0.1	1.6
Pinus virginia Mill.	0.1	1.7
Tsuga canadensis (L.) Carr.	0.3	3.7
Acer nigrum Michx.f.	0.0	0.3
Acer pensylvanicum L.	0.0	0.2
Acer rubrum L.	1.5	29.0
Acer saccharum L.	1.1	14.7
Aesculus octandra Marsh.	0.1	1.4
Ailanthus altissima (Mill.) Swingle	0.0	0.1
Amelanchier spp.	0.0	0.4
Betula alleghaniensis Britton	0.0	0.2
Betula lenta L.	0.3	4.9
Betula nigra L.	0.0	0.1
Carpinus caroliniana Wait.	0.0	0.2
Carya cordiformis (Wangenh.) K.Koch	0.2	2.1
Carya glabra (Mill.) Sweet	0.9	12.5
Carya laciniosa (Michx.f.)Loud.	0.1	1.0
Carya ovata (Mill.) K. Koch	0.2	2.5
Carya tomentosa Nutt.	0.5	7.6
Celtis occidentalis L.	0.0	0.2
Cercis canadensis L.	0.0	0.4
Cornus florida L.	0.0	0.9
Diospyros virginినana L.	0.0	0.1
Fagus grandifolia Ehrh.	2.3	17.5
Fraxinus americana L.	0.2	2.7
Fraxinus pennsylvanica Marsh.	0.1	1.7
Gymnocladus dioicus (L.) K.Koch	0.0	0.1
Juglans nigra L.	0.1	0.9
Liquidambar styraciflua L.	0.0	0.3
Liriodendron tulipifera L.	3.1	33.0
Magnolia spp. L.	0.0	0.2
Magnolia acuminata L.	0.2	3.5
Magnolia macrophylla Michx.	0.0	0.2
Magnolia fraseri Walt.	0.0	0.5
Morus rubra L.	0.0	0.4
Nyssa sylvatica Marsh.	0.4	8.0
Ostrya virginiana (Mill.) K.Koch	0.0	0.2
Oxydendrum arboreum (L.) DC.	0.2	8.4
Platanus occidentalis L.	0.1	0.9
Prunus serotina Ehrh.	0.0	0.6

continued

Table 1.—continued.

Quercus alba L.	2.7	26.7
Quercus coccinea Muenchh.	1.1	8.6
Quercus falcata Michx.	0.1	0.7
Quercus muehlenbergii Engelm.	0.0	0.3
Quercus palustris Muenchh.	0.0	0.1
Quercus prinus L.	3.6	34.1
Quercus rubra L.	1.3	10.9
Quercus stellata Wangenh.	0.1	1.0
Quercus velutina Lam.	1.8	12.9
Robinia pseudoacacia L.	0.1	1.7
Sassafras albidum (Nutt.) Nees	0.2	5.6
Tilia americana L.	0.5	6.0
Ulmus americana L.	0.0	0.2
Ulmus rubra Muhl.	0.0	1.0
Unidentified trees	0.0	0.4
All species	23.9	276.7

0.0 = a value of > 0.0 but < 0.1 for the cell.

Table 2.—Stand attributes by aspect class on the Appalachian Plateaus Province of eastern Kentucky

Stand attribute	Aspect					
	NE[1]	N + E[2]	NW + SE[3]	W + S[4]	SW[5]	All
Number of plots	17	60	44	42	23	186
Basal area	25.1	24.1	25.4	21.9	23.5	23.9
Density	293.9	282.8	286.3	256.0	280.0	278.2
McIntosh Evenness	0.76	0.85	0.83	0.85	0.85	0.84
Species richness	7.8	8.0	7.1	6.7	7.3	7.4

[1] NE = 22.5 – 67.4 (degrees azimuth)
[2] N = 337.5 – 22.4; E = 67.5 – 112.4 (degrees azimuth)
[3] NW = 292.5 – 337.4; SE = 112.5 – 157.4 (degrees azimuth)
[4] W = 247.5 – 292.5; S = 157.5 – 202.4 (degrees azimuth)
[5] SW = 202.5 – 247.4 (degrees azimuth)

Most of the study plots (119) were on steep slopes (> 40 percent) (Table 3). Basal area, density, and species richness were highest on plots with slopes of 20-29 percent. Plots with slopes of 0-9 percent had the lowest average basal area and density (Table 3).

Of the 56 tree species tallied on the 186 study plots, *Q. prinus* had the highest basal area, averaging 3.6 m^2 ha^{-1}. (Table 1). Ranked next were *L. tulipifera, Q. alba*, and *F. grandifolia* with 3.1, 2.7, and 2.3 m^2 ha^{-1}, respectively. These four species accounted for 49 percent of total basal area across all plots.

Of the 3,480 trees ≥ 12.7 cm d.b.h. 329 were >50 cm d.b.h. Forty-one were >70 cm and 13 were >80 cm d.b.h. Ranked by d.b.h. the five largest trees were *Q. coccinea* (one tree), *A. saccharum* (one), and *F. grandifolia* (three). Their respective diameters were 122.2, 109.2, 97.0, 93.2, and 89.9 cm.

Table 3.—Stand attributes by slope class on the Appalachian Plateaus Province of eastern Kentucky

Stand attribute	Slope (percent)						
	0 - 9	10 - 19	20 - 29	30 - 39	40 - 49	≥50	All
Number of plots	9	14	17	27	49	70	186
Basal area (m^2 ha^{-1})	16.6	24.9	27.5	24.2	22.3	24.8	23.9
Density (stems ha^{-1})	191.7	274.0	321.9	294.7	259.8	286.2	278.2
McIntosh Evenness	0.84	0.85	0.82	0.82	0.85	0.83	0.84
Richness	7.4	7.2	8.4	7.1	7.1	7.5	7.4

The highest basal area recorded on any plot was 40.9 m^2 ha^{-1}. Overall, there were only 15 plots with a basal area >35.0 m^2 ha^{-1}. Highest ranked of these were four in the *F. grandifolia* community, three in the *Q. prinus* community, and two in the *A. rubrum* communities.

The highest q.m.d. recorded on any plot was 46.5 cm, which occurred in a *F. grandifolia* community on a slope of 24 percent at an aspect azimuth of 321 degrees. Only nine plots in the study population had a q.m.d. >40.0 cm.

The maximum species richness (14 species per plot) was recorded on two plots. Including the latter two plots, only 18 plots had more than 10 species: one plot with 13 species, four plots with 12 species, and 11 plots with 11 species.

Using a monomial naming convention, 10 forest communities were recognized in the study population (Table 4). The *Q. prinus* community was the most prevalent, occurring on 39 plots. The next most common communities were *F. grandifolia* , *L. tulipifera*, and *Q. alba*, occurring on 29, 27, and 26 plots, respectively. The *L. tulipifera* and *Q. velutina* communities had the lowest degree of species evenness, where both equaled 0.77. Lowest species richness was in the *F. grandifolia* and *Q. rubra* communities. Highest species richness was in the *Q. velutina* and *A. rubrum* communities (table 4). The highest average basal area was in the *A. rubrum* community, 27.0 m^2 ha^{-1}. The *C. glabra* and *Q. alba* communities had the lowest average basal areas, 22.1 and 22.7 m^2 ha^{-1}, respectively. While the *F. grandifolia* community had a relatively low basal area (22.8 m^2 ha^{-1}), it had the only plot with a q.m.d. of 46.5 cm, the highest recorded. Additionally, there were four plots in this community with a basal area >35.0 m^2 ha^{-1}.

DISCUSSION

The average basal area of the study plots was at the lower end of the range of older, mature stands in the Appalachian Mountains and Appalachian Plateaus Province. Stand basal area for eastern deciduous mesic old growth forests is typically in the range of 25 to 32 m^2 ha^{-1} (Held and Winstead 1975). Martin (1992) reported averages of 25 m^2 ha^{-1} at Lilley Cornett Woods on the southeast edge of the Cumberland Plateau in Kentucky. McCarthy and others (1987) reported an average of 29.6 m^2 ha^{-1} with a range of 21.7 to 41.0 m^2 ha^{-1} in Hawk Woods on the unglaciated Allegheny Plateau in southeast Ohio. In another study in Lilley Cornett Woods, Muller (1982) documented 27.0 m^2 ha^{-1} in the old-growth portion and 24.0 m^2 ha^{-1} in the secondary forest. It is important to note that many of the studies used in comparison had a minimum threshold for trees of 10 cm d.b.h. versus 12.7 cm d.b.h. in this study. In addition, many studies aggregated several sample plots when describing specific communities whereas this study had one sample plot representing each sample location.

Table 4.—Attributes of 10 forest communities on the 186 study plots on the Appalachian Plateaus Province of eastern Kentucky. The comparison is made between application of a monomial name versus binomial name (see text for details)

Forest community	Plots on which species is dominant	Forest communities resulting from use of a monomial name	Forest communities resulting from use of a binomial name	Percentage of plot basal area accounted for by the top 4 species			Richness	Evenness	Basal area
	No.	No.	No.	Min.	Max.	Avg.			(m^2 ha^{-1})
Chestnut oak	39	1	11	69	100	90	7.1	0.83	25.0
American beech	29	1	12	69	100	89	6.7	0.85	22.8
Yellow-poplar	27	1	14	73	100	89	7.4	0.77	23.4
White oak	26	1	9	62	100	87	7.2	0.84	22.7
Scarlet oak	12	1	9	75	95	81	7.5	0.87	24.1
Black oak	11	1	8	63	98	88	8.9	0.77	23.9
Northern red oak	9	1	6	71	100	89	6.8	0.88	23.7
Sugar maple	7	1	6	79	100	82	7.1	0.84	25.4
Red maple	7	1	6	68	94	85	8.6	0.83	27.0
Pignut hickory	4	1	4	75	96	85	8.0	0.84	22.1
Misc. others	15	--	--	--	--	--	--	--	--
All plots	186	10	85	54	100	88	7.4	0.84	23.9

The average density of the study plots was comparable to that reported in other studies in mature Appalachian and mixed mesophytic forests. Parker (1989) reported a range of 151 to 427 trees ha^{-1} while Martin (1992) documented > 250 trees ha^{-1} at Lilley Cornett Woods. McCarthy and others (1987) reported an average of 371 trees ha^{-1} at Hawk Woods in southeast Ohio with a range of 250 to 445 trees ha^{-1}. Muller (1982) reported an average of 428 trees ha^{-1} in the old-growth forest and 529 trees ha^{-1} in the secondary forest of Lilley Cornett Woods.

Although the species that were most dominant in the study plot population were similar to other studies, the ranking was slightly different. McCarthy and others (1987) ranked *Q. alba* as number one followed by *A. saccharum, L. tulipifera, Q. prinus*, and *Q. rubra*. Muller (1982) ranked *F. grandifolia* first, followed by *Q. prinus, A. saccharum*, and *A. rubrum* in an old-growth forest. In a secondary forest he ranked *F. grandifolia* as first, then *Q. prinus, L. tulipifera*, and *A. rubrum*. Galbraith and Martin (2005) reported six species that comprised 60 percent of total species importance: *F. grandifolia, Tsuga canadensis, A. rubrum, Q. alba, A. saccharum*, and *Q. prinus*. McEwan and Muller (2006) reported the top dominants as *F. grandifolia, Q. prinus, L. tulipifera*, and *Q. alba*. Braun (1942) noted that the mixed mesophytic forest is poorer on the Cumberland Plateau than in the Cumberland Mountains. In comparison, the forests of the plateau are more dominated by *F. grandifolia, Q. alba*, and *Q. prinus*. There is less dominance from *Tilia heterophylla*, *Aesculus octandra, A. saccharum, L. tulipifera*, and *Q. rubra*. Noticeably absent from the 186 study plots was *T. heterophylla*. Additionally, *Aesculus octandra* occurred on only nine plots. These two species are key indicators of Braun's mixed mesophytic forest association (Braun 1950).

Because of the subjectiveness in naming and describing forest communities, no meaningful comparisons could be made with existing studies. Unfortunately, vegetation classification suffers from overstatement, ambiguity, and misinterpretation. Most approaches are based on conceptions of pattern and overall character of the vegetation; therefore, any interpretation will often be based on personal choice, intuition, subjectivity, and experience (Shimwell 1971).

The nomenclature system used to identify specific communities can often cause problems and confusion, especially when trying to identify communities to finer degrees or levels. Baker (1950) lists several good reasons for this confusion: (1) the boundaries between communities may be vague; (2) extensive unlisted or unrecognized mixtures may occur; (3) local or rare types may not be included in the naming classification being used; and (4) it is difficult to determine whether a local area with a particular species is unique or just a phase of a broader mixed type. In addition, the various stages of stand succession are not always considered in naming or typing conventions.

Any, or all, of these issues may lead to inconsistencies between authors, resulting in descriptive work that is not comparable. I chose to use the monomial approach in naming the communities in this study because they are easier to consistently identify on the ground and classify using plot data. When the binomial naming convention is used, the number of unique forest communities balloons quickly to an unmanageable level; in this study, 85 possible communities would have resulted (Table 4). Subjective decisions would have been required on how to lump this large number of groups into meaningful and comprehensible communities. In addition, with sampling regimes that cover larger and larger areas, classification becomes complex because of the different roles the same character or indicator species may play in different habitats (Van der Maarel 2005).

Based on the plot data in the study, some of these stands may qualify as old-growth or late successional-mature forests. This conclusion holds especially true for the plots with trees >75 cm d.b.h. and basal areas >35 m^2 ha^{-1}. Martin (1975) suggests at least seven trees ha^{-1} >75.0 cm d.b.h. to indicate old-growth status. Because of the ruggedness of topography on the Cumberland and Allegheny Plateau (slopes >40 percent), some of these sites probably escaped logging. However, many did not and the impacted stands are still recovering from logging disturbance as well as the loss of *Castanea dentata*. This condition, plus burning and continued high grading, left some stands with poorly interpretable species patterns (Muller 1982). Natural disturbance is also an important factor in these systems, especially on steep slopes. Windthrow and slope slides are a significant component in modifying stand age and composition (Herman and See 1973). Unfortunately, it is not possible to interpret complexities of stand disturbance into the far past (>20 years) with FIA data.

This study used data from a very large landscape-scale sampling scheme. The sample provides a good account of current forest conditions over a large geographic area, which is in contrast to most studies where unique areas are selected for concentrated study. It is important to be mindful of this difference when comparing study results. The FIA data do provide valuable information on extent of forest conditions across a very wide area. Future studies with this dataset across the Appalachian Plateaus Province will develop more detail regarding the actual areas covered by different forest conditions along with refined forest community analysis. In addition, as future surveys are completed, plots can be tracked over time, providing a valuable record of trends in forest attribute dynamics.

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TWENTY-YEAR-OLD RESULTS FROM A BOTTOMLAND OAK SPECIES COMPARISON TRIAL IN WESTERN KENTUCKY

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Abstract.—A 20-year-old trial of five bottomland oak species (cherrybark, Nuttall, pin, water, and willow oaks) located in western Kentucky showed little difference in survival and growth but considerable difference in form characteristics. Mortality was highest between ages 1 and 3 years during plantation establishment until tree-to-tree competition began increasing between the ages of 10 and 20 years. Willow oak had the highest survival, water oak the overall best growth and cherrybark oak the best form. At age 20 the mean diameter at breast height for all species combined was 7.1 inches and their mean height was 60 feet. The relatively small tree diameters are probably the result of too many trees per acre. While suppressed trees quickly fall out of the stand, the high number of living trees per acre has perpetuated smaller crowns, a thick leaf layer, and low forest floor sunlight, resulting in very little invasion by grasses and forbs as well as virtually no acorn production. With the exception of pin oak, water oak was significantly taller than all of the other species. Water oak was also larger than all other species tested. At age 20, the various species within the study have begun to exhibit those factors that would allow determination of stand manipulation timing and scale to provide not only timber revenue but wildlife values. A discussion concerning oak species plantings examines means by which young bottomland oak stands may be manipulated to accomplish multiple goals.

INTRODUCTION

High quality bottomland oaks can provide substantial timber revenue as well as wildlife benefits. But, like other hardwoods, it is critical that the correct oak species are matched to the site. Artificial regeneration of hardwoods has primarily focused on single-species plantings (Meadows and Hodges 2004, Siry 2002). This approach is advantageous for early successional shade-intolerant species, such as eastern cottonwood (*Populus deltoides* Bartr.ex Marsh.), sycamore (*Platanus occidentalis* L.), and sweetgum (*Liquidambar styraciflua* L.), but it is much more difficult for species such as oaks that are partially shade tolerant to compete with the growth rates of those shade-intolerant species. Even when soil/site conditions are properly matched to the species, rapidly growing early successional species will survive and reach their full growth potential only when competing vegetation is held in check during the first 2 to 3 years of establishment. Early successional, shade-tolerant bottomland species also have high nutrient and water demands, which if not met will lead to slow growth or will stress the trees to the point where disease may result in significant mortality. Assuming growth rates are suitable for a positive return on investment for cottonwood, sycamore, or sweetgum, pulpwood would be the primary market as intensive bottomland hardwood monocultures focus on biomass growth and not wood quality characteristics (Robison and others 1998, Scott and others 2002, Stanturf and Portwood 1999). In contrast, oaks have slower early growth rates which are not conducive to a positive return on investment from pulpwood. However, if timber quality is high, bottomland oak plantations can be profitable if held for longer rotations. If timber quality is lacking, though, a long rotation will still yield only a limited revenue stream.

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The original objective of this study was to determine the feasibility of growing oaks in plantation culture on bottomland sites as an alternative to intensive plantation management of rapidly growing hardwood species such as cottonwood, sycamore, or sweetgum. Therefore, the key was to determine which species of oaks will not only survive and grow at an acceptable rate but will also be of the quality needed for higher rates of return. This study was originally focused on defining the financial feasibility of a pulpwood rotation for oaks, but the secondary objective was to determine a financial return from veneer or sawtimber.

METHODS AND STUDY AREA

Open-pollinated seed from seven mother trees were collected during the fall of 1985 from each of five species of red oaks: cherrybark oak (*Quercus pagoda* Raf.), Nuttall oak (*Q. texana* Buckl.), pin oak (*Q. palustris* Muenchh.) water oak (*Q. nigra* L.), and willow oak (*Q. phellos* L.). Cherrybark oak originated from west Tennessee (Ames Plantation), Nuttall oak from north-central Mississippi, pin oak from western Kentucky, water oak from the Mississippi Delta near Stoneville, MS, and willow oak from western Kentucky.

Following collection, acorns were immersed in water to facilitate removal of damaged or insect-infested seed (acorns that floated). Sound seed were drained and stored in sealed plastic bags at approximately 35 °F until sowing. The bags were opened monthly and seed were washed and re-immersed in water as an additional means of discarding nonviable seed. Prior to sowing, each seed lot was re-immersed and germinated on blotter paper in shallow metal trays. Every third day, germinated seed were sown at a rate of five seedlings per square foot at the J. P. Rhody Kentucky State Nursery, near Gilbertsville, KY. All of the seed were sown between April 14 and April 23, 1986. Nursery practices included fertilization with ammonia nitrate, foliar sprayings of chelated iron, and lateral root pruning. Chelated iron was applied following each flush of growth. Lateral root pruning designed to create a more compact root system was done three times during the growing season with colters affixed to a tractor toolbar. Seedlings were lifted on February 8, 1987. Only seedlings having root collar diameters between ½-inch and ¾-inch, with six to eight first-order lateral roots were included in the test. In addition, similar seedlings of all species were grouped by replication, thus minimizing differences within replication. Seedlings were bundled and stored by plot and replication, and stored in bags at 35 °F until planting.

The test site is located in Ballard Co., KY. Soil type is described as a Falaya-Collins silt loam, with high available moisture, moderate permeability, moderate natural fertility, medium organic matter content, and strongly acidic pH (Humphrey 1976). Periodic flooding of the test site for various lengths of time can occur during the winter and spring as the result of high water conditions on the lower Mississippi River. Stand history indicated that the area was a native bottomland hardwood stand containing various species of red oaks, eastern cottonwood, boxelder (*Acer negundo* L.), green ash (*Fraxinus pennslyvanica* Marsh.), silver maple (*A. saccharinum* L.), sugarberry (*Celtis laevigata* Willd.), shagbark hickory (*Carya ovata* (Mill) K. Koch), and sweetgum. In 1979, the natural stand was cleared and an eastern cottonwood plantation was established. The stand never received lime or fertilization, and after six years the stand did not exhibit sufficient stocking levels or growth to be economically viable. Consequently, the trees were sheared, piled, and burned. Site preparation included disking, row marking, and slitting at a spacing of 9 x 9 ft.

The experimental design is a randomized complete block consisting of six blocks and five oak species arranged in 49-tree block plots. There were only enough Nuttall oak seedlings for two complete blocks. Research personnel planted the test on March 27, 1987. Herbaceous and vine competition was controlled during the first and second year by disking. First-year maintenance was excellent. Measurements included survival and height at ages 1, 3, 5, 10, 15, and 20 years while diameter at breast height (d.b.h.) was taken at

Table 1.—Test survival for all species. Estimated trees per acre based on survival and phases that affect survival during the 20 years of the 1987 Oak Species Comparison Trial located on a bottomland site in Ballard Co., KY

	Age (yrs)	Survival (%)	Mortality (no.)	Tree/Acre (no.)
Phase I[1]	1	98	25	527
	3	94	45	508
Phase II	5	94	1	508
	10	94	8	505
Phase III	15	90	48	484
	20	78	148	422

[1]The phases shown define specific points along a timeline during the life of this specific plantation. Phase I is the establishment phase, Phase II is the rapid-growth phase and Phase III is the intensive tree-to-tree competition phase.

ages 5, 10, 15, and 20 years. Heights were measured to the nearest tenth of a foot using poles at ages 1, 3, and 5 years. Heights at ages 10, 15, and 20 years were measured using an Impulse Laser to a tenth of a foot. Diameters were measured at ages 10, 15, and 20 years using a D-tape to the nearest tenth of an inch. Form defects such as crooked stems, forks, multiple stems and a variety of stem problems were also tallied at age 20. Survival data were transformed using arcsine transformation. Statistical analysis using GLM procedure on a plot mean basis to test for difference among species, and Duncan's Multiple Range test was used for mean comparisons ($p < 0.05$). All analyses were completed using SAS/STAT software, version 9.1 of the SAS System for Windows (SAS Institute, Inc., Cary, NC, 1999-2000). Pearson's Correlations were used to determine correlation coefficients within a specific trait across age groups using age 20 years as the desired selection age.

RESULTS

Survival

All Species. First-year survival was 98 percent, providing an excellent opportunity to determine factors affecting the number of trees per acre as age increases. By age three, mean survival dropped to 94.5 percent and remained fairly constant though age 10, where survival was nearly 94 percent (Table 1). Through age 10, the number of trees per acre was still high at approximately 500 trees per acre. Survival declined four percent between ages 10 and 15 and dropped nearly 13 percent between ages 15 and 20. Accordingly, the number of trees per acre also dropped to 422 trees as survival declined to 78.4 percent. Another aspect of Table 1 is the grouping of ages by what is termed phases. In this manner, specific ages are grouped together and identified as phases, which define the factors that play a critical role in survival and growth (Table 1).

Individual Species. Significant survival differences were noted among the various oak species after the first year, yet there was only a 3.4-percent range in survival resulting from Nuttall oak exhibited 100 percent survival while water oak was the lowest at 96.6 percent (Table 2). All of the species showed a decline in survival between ages 1 and 3 years with Nuttall and pin oak having the highest survival at 97 percent and water oak the lowest at 88 percent. Water oak survival remained significantly lower than the other species from age three to age 20 (Table 2). Survival among all species remained constant between ages 3 and 10

Table 2.—Survival of oak species at ages 1, 3, 5, 10, 15, and 20 years found in the 1987 Oak Species Comparison Trial located on a bottomland site in Ballard Co., KY

	Percent Survival ----------------Age---------------- (yrs)					
Oak Species	1	3	5	10	15	20
Willow	99ab[1]	96a	96a	96a	94a	86a
Cherrybark	98bc	96a	96a	96a	90a	77ab
Water	97c	88b	88b	86b	82b	70c
Pin	99abc	97a	97a	96a	93a	80ab
Nuttall	100a	97a	97a	97a	94a	83a

[1]Means not sharing the same letter within a column for a given age indicate significant differences at α=0.05.

Table 3.—Species means for total height at ages 1, 3, 5, 10, 15, and 20 years and diameter at ages 10, 15 and 20 years for the 1987 Oak Species Comparison Trial located on a bottomland site in Ballard Co., KY. Diameter refers to d.b.h.

	Total Height (ft) ------------ Age ------------						Diameter (in) ---- Age ----		
Oak Species	1	3	5	10	15	20	10	15	20
Willow	2.3a[1]	8.8a	13.4a	32.8a	46.9b	60.8bc	4.6a	6.0a	7.3b
Cherrybark	1.7c	5.7d	10.4d	28.4c	45.9b	60.5c	3.8b	5.6b	7.1b
Water	1.7c	7.8b	12.6b	32.8a	48.3a	63.1a	4.5a	6.1a	7.9a
Pin	1.9b	8.1b	13.7a	33.4a	48.3a	62.0ab	4.4a	5.7b	7.0b
Nuttall	1.9b	7.1c	11.9c	29.7b	43.0c	55.3d	4.0b	5.2c	6.3c

[1]Duncans Multiple Range Test where different letters within a column for a specific trait designate significant differences among means at α=0.05

years. Changes in survival between ages 10 and 15 were fairly consistent among the various oak species with cherrybark exhibited the greatest change with a 6 percent decline in survival and willow oak the least with a 2 percent decline. By age 20, survival across the five oak species was substantially lower for all species when compared to age 15 survival. Willow oak had the smallest decrease in survival at only 8 percent while cherrybark oak had the greatest decrease at nearly 14 percent.

Height and Diameter

All Species. Means for total height at ages 1, 3, 5, 10, 15, and 20 years were 1.9, 7.6, 12.5, 31.6, 47.0, and 61.1 ft, respectively. Means for d.b.h. at ages 10, 15 and 20 years were 4.3, 5.8, and 7.2 inches, respectively. Once the seedlings were established and had attained sufficient height to overtop weed competition, the observed tree growth was largely a response to the inherent site conditions in the context of the weather and climate over the study period. The growth response serves as a relative index of suitability of these five oak species to the specific soil/site conditions of the test site.

Individual Species. Oak species performance through time is shown in Table 3. Significant differences among species were noted for total height and diameter at all ages. Willow oak was significantly taller than all species at age 1 year, but by age 10 it was not significantly taller than water oak or pin oak. Although cherrybark oak and water oak total heights were not significantly different at age 1 year, they were by age

Table 4.—Height and diameter growth by species for all ages of the 1987 Oak Species Comparison Trial located on a bottomland site in Ballard Co., KY

	Height Growth (ft) ------------ Age (years) --------					d.b.h. Growth (in) --Age (years)--	
Oak Species	1-3	1-5	5-10	10-15	15-20	10-15	15-20
Willow	6.5a[1]	11.1b	19.4b	13.8c	12.9ab	1.4b	1.1b
Cherrybark	3.9d	8.6d	18.0c	16.8a	13.3a	1.6a	1.1b
Water	6.0b	10.8b	20.0a	15.2b	13.5a	1.5a	1.4a
Pin	6.1b	11.7a	19.7ab	14.7b	12.7ab	1.3c	1.0bc
Nuttall	5.2c	10.0c	17.7c	13.1c	12.3b	1.1d	0.9c

[1]Duncan's Multiple Range Test where different letters within a column for a specific trait designate significant differences among means at $\alpha=0.05$

three. In fact, by age 20, water oak attained the greatest mean height of approximately 63 ft. At age 20, cherrybark oak was not significantly different from willow oak and was only significantly taller than Nuttall oak. Nuttall oak was significantly shorter than the other four oak species at ages 15 and 20 years. A range of 8 ft separated the tallest species (water oak) from the shortest species (Nuttall oak). There were numerous individual trees of water, pin, and cherrybark oak that had heights greater than 70 ft at age 20. Pin oak had the greatest number (18) of trees taller than 70 ft followed by cherrybark and water oak (16 trees each).

Differences in mean diameter among four oak species, excluding Nuttall oak, were less than 1 inch. The small diameters are probably the result of inter-tree competition due to the tight spacing and high survival rates. Cherrybark oak and water oak were the only two species exhibiting more than 10 trees greater than 10 in diameter, with a total of 15 and 19 trees, respectively.

The trend in height and diameter growth indicates a rather slow establishment period between ages 1 and 3 years, defined as Phase I (Table 1). Annual height growth peaked for all species between the ages of 5 and 10 years with water oak averaging 4 ft of height growth per year (Table 4). Although height growth of cherrybark oak started slowly, growth rates increased through time, and from age 15 on cherrybark ranked among the fastest growing species. All five oak species showed a slow but continual decline in mean growth rates from their respective peak growth rates between the ages of 5 and 10 years. However, even at the latest measurement (age 20 years), all of the oak species continued to show double-digit mean growth rates over the previous 5-year period resulting in approximately 2.5 ft of height growth per year.

Because d.b.h. measurements were taken only at ages 10, 15, and 20 years, diameter growth can be compared only over the last 10 years of the study. Average growth was greatest for all species between ages 10 and 15 years (Table 4). Diameter growth between ages 15 and 20 years was slower for all species. Except for Nuttall oak, all species averaged greater than 1-inch of diameter growth between ages 15 and 20 years.

Table 5 shows correlations for total height at ages 1, 3, 5, 10, and 15 years with age-20 total height. Correlations between age 1 year total height and age 20 total height for all oak species were very poor, with Nuttall oak exhibiting a negative correlation. As expected, correlations strengthened as age increased toward age 20. By age 10, trees exhibited a fairly strong correlation with their observed height at age 20. Although not shown, correlations between earlier diameters and age-20 diameters were similar to the correlations for height but based on a more limited time span since diameters were not measured until age 10.

Table 5.—Total height-age correlations with age-20 total height for all species in the 1987 Oak Species Comparison Trial located on a bottomland site in Ballard Co., KY

Oak Species	Age 1	Age 3	Age 5	Age 10	Age 15
Willow	0.31[1]	0.58	0.65	0.78	0.78
Cherrybark	0.26	0.57	0.68	0.78	0.75
Water	0.23	0.45	0.56	0.62	0.63
Pin	0.18	0.42	0.61	0.75	0.82
Nuttall	-0.04	0.58	0.80	0.85	0.85

[1]Pearson correlation coefficients

DISCUSSION

Survival

Survival through time provides insight into the processes affecting survival and growth. The three phases listed in Table 1 can be categorized by those factors that affect both survival and growth. For this oak trial and many other oak plantations, the first 3 years can be termed the establishment phase (i.e., Phase I) where factors such as seedling quality, site preparation, planting quality, and competition control are critical to survival. Although environmental conditions cannot be controlled, we can minimize their effect on survival by maximizing seedling quality, site preparation, planting quality, and competition control. Phase I sets the stage for the following phases and the overall performance of the plantation. If any of the above factors are neglected, the plantation will become stressed, resulting in lower survival and reduced growth. It is important to note that oak species in this trial were, in general, suited to the soil type found on this site. However, water oak and Nuttall oak are southern species not found in western Kentucky. Phase II is defined as the rapid growth stage where oak seedlings have reached heights above the competing herbaceous vegetation and started to increase in crown size. Root systems in Phase II are also large enough to accelerate growth over the establishment phase. As shown in Table 1, mortality during this stage is minimal as the trees have out-competed the herbaceous material and are now on their way to fully occupying the site. Phase III can be described as the inter-tree competition stage, where, based on growth rates, trees are competing against each other for site resources. It is during this intense tree-to-tree competition stage that mortality increases as the more thrifty trees began to gain dominance resulting in mortality of slower growing trees.

Site conditions, seedling quality and planting quality were excellent for survival and growth. Herbaceous competition clearly had only a minor impact on survival. Between ages 1 and 3 years, an additional 45 trees were lost in the test, reducing overall survival to approximately 95 percent. The majority of the mortality during this period was observed in water oak. This southern species may be more susceptible to the cooler temperatures of western Kentucky. By age 3 years, survival of water oak was significantly lower than the other four oak species, declining from 96 percent at age 1 year to 88 percent at age 3 years (Table 2). However, age-5 and age-10 survival showed very little change to that of age-3 survival, indicating that all five species were able to cope with the climatic conditions of the test site. Between ages 10 and 15 years, tree-to-tree competition began to impact the stand and mortality increased. This trend was somewhat more evident in blocks that were on a slightly better potion of the site. Even minute site differences can lead to differences in growth and survival. This finding emphasizes the need to carefully select the hardwood species for specific differences even within small acreages.

Extremely intense tree-to-tree competition was the norm between ages 15 and 20 years, where mortality increased nearly threefold from 48 trees at age 15 years to 148 at age 20 years. All oak species, with the exception of willow oak (8 percent decrease in survival), showed double-digit decreases in percent survival between the ages of 15 and 20 years. In addition there were 102 trees designated as suppressed trees during age 20 measurements. Factoring these trees into expected 5-year survival percentages indicates that survival will probably decline to below 70 percent. The number of trees on a per-acre basis for age 25 will be approximately 375 trees or less. By all indications the number of trees in the trial on a per-acre basis is higher than necessary for sawtimber objectives. However, Kennedy (1992) cited several publications that showed similar number of trees per acre for various species of bottomland oaks, such as cherrybark, water, and Nuttall oak. The data suggest that in this specific trial, removal of less desirable trees would be beneficial for additional growth to the remaining crop trees.

A potential solution would be to apply a thinning to these types of plantations. One problem associated with thinning at earlier ages is the cost, as the majority of the material would be precommercial unless whole-stem chipped. But, if landowner objectives included both timber value and wildlife benefits, early thinning might be justified. An alternative is to inject unwanted trees with herbicide, thus creating the same effect as thinning without the possibility of mechanical damage to reserved trees. In this manner, less desirable poor-quality trees would be removed, while some large, heavy-crowned trees would be left for mast production. This system could increase the value of the remaining high-quality stems by providing more growing space and opening the stand to more sunlight. Increased sunlight to the forest floor would then contribute to the production of grasses and forbs for wildlife species such as deer and turkey.

Height and Diameter Performance

The test site can be classified as an excellent hardwood site. It is located in western Kentucky on Mayfield Creek, which flows into the Mississippi River approximately 5 miles from the test site. Although these sites are subject to periodic flooding, similar sites have been cleared for agricultural production as numerous fields along the same creek are in corn and soybean production. Using the Baker-Broadfoot System (1979) of assessing site quality, it was determined that sycamore and sweetgum were the species best suited to this site. Although cottonwood and sycamore were operationally established on the site by Westvaco, it was later determined through testing that the best suited species were oaks and sweetgum.

For this study, growth of Nuttall oak growth seems the most puzzling. Based on experience, I expected an increased growth rate resulting from moving a southern species north, as observed in water oak. This type of growth gain has been noted in numerous hardwood genetic studies where movement of southern material northward results in faster growth rates (Gwaze and others 2003, Kriebel 1988, Rousseau 1987, 1989, Steiner and others 1985). In addition, the site is a typical pin oak site which seems to occupy the same niche in more northern geographic areas that Nuttall does in southern areas. The poorer performance in this study may be related to the fact that Nuttall source was from a much narrower genetic base due to the limited number of trees collected. However, this aspect may have been a positive one rather than a negative one, but in this case it does seem to be partially attributed to poor genetics.

Willow and pin oaks are frequently found on this type of site in western Kentucky whereas cherrybark oak would occur very infrequently. Cherrybark oak is typically found on western Kentucky sites that have greater nutrient capacity and increased soil aeration. I expected both willow and pin oak to perform well on this particular site but for cherrybark to suffer from poor soil drainage. Comparisons between a

Figure 1.—Difference in self-pruning ability of cherrybark oak (left) and pin oak (right) at age 20 in the 1987 Oak Species Comparison Trial located on a bottomland site in Ballard Co., Kentucky

1987 cherrybark oak progeny test planted on a loess site in western Kentucky at the same spacing and the cherrybark in this trial showed the progeny test to be approximately 6 ft taller and a half an inch greater in diameter at age 20 years (Adams and others 2007). At age 20 years, mean height and diameter for the progeny test was 66 ft and 7.6 in, respectively. In the current study, mean species height among cherrybark, pin, water and willow oak differed only slightly at age 20 with approximately 2.5 ft between the tallest (water oak) and the shortest species (cherrybark oak). This difference represents approximately a single year of height growth. Similar results were found for diameter, where again water oak and cherrybark oak represent the largest and the smallest species, respectively. This difference was 0.8 in, which on average represents approximately a 3- to 4-year separation. The anticipation was that the mean diameter at age 20 years would be approaching 10 in. In fact, only 7 and 9 percent of the trees in the cherrybark and water oak plot exhibited d.b.h greater than 10 in at age 20. The high stocking levels maintained through age 20 apparently have greatly reduced diameter growth. However, the stocking levels allowed for early capture of the site by the oaks and the ability to express inherent stem form. Increasing growing space at earlier ages may have allowed larger trees and better possibilities of a commercial thinning.

While stem quality data were collected for all species, the most dramatic differences were noted between cherrybark oak and water oak. These data provide insight into the possible revenue from quality stems. The number of defects noted between water oak and cherrybark oak is much greater than the few additional years needed for cherrybark to attain the same height and diameter. One of the most visible early differences noted was the excellent self-pruning ability of cherrybark in comparison to other species tested (Fig. 1). Even at age 20 years, pin oak and willow oak still have a large number of very low branches attached to the stem. During data collection, tree form and timber quality characteristics were also recorded and included forking, ramicorn branching, multiple tops, excessively crooked stems, double stems, and any type of bole damage. Water oak was found to have over eight times the number of defects as cherrybark oak at age 20 years. This striking difference in form quality between these two species indicates that if the site is suitable for cherrybark oak, it would be advantageous to plant this species rather than water oak.

If an intermediate thinning is needed, at what age can we be fairly confident of selecting the right trees for release? Correlations listed in Table 5 suggest that when total height at age 20 years is the desired trait, selection at ages 1 and 3 years should be avoided. However, by age 10 correlations are high enough for all species except water oak, that a manager can be fairly confident in selecting the correct crop trees for release. Allowing the stand to grow to age 10 before thinning places the desired trees in a dominant canopy position and may greatly reduce epicormic branching. Other positive aspects from an early thinning would be increased crown size, greater acorn production and increased sunlight to the forest floor, allowing the production of grasses and forbs for wildlife.

Artificial regeneration of oaks remains problematic as it encompasses site preparation, seedling quality, competition control, and other critically timed silvicultural treatments that are key to survival and rapid growth. In many circumstances the production of quality stems is critical to a greater financial return, yet typical lower numbers of seedlings per acre result in poor stem-form characteristics while higher numbers reduce growth and dictate intermediate costly steps. While this study was not designed to evaluate planting densities, I think that the higher density of 538 trees per acre, as shown in this study, provides the ability to quickly capture the site and avoid the negative effects of open grown trees when log quality is the goal. In this study, as with others, a higher number of stems per acre appears to be warranted to ensure sufficient numbers of quality trees at harvest. Currently, it has been proposed that for bottomland oak plantations there should be approximately 400 to 450 stems per acre at age 3 years (J.D. Hodges, personal communication, meeting for the Lower Mississippi River Valley Science Synthesis).

Related to the number of trees per acre needed as these types of plantations move through time is the genetic component. Currently, there is no available improved southern bottomland oak genetic material. As such, this impacts the number of trees planted on a per-acre basis as greater tree numbers provide possible alternatives in selection for log quality in our crop trees.

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CONTRIBUTION OF STUMPS TO CARBON AND NITROGEN POOLS IN SOUTHERN APPALACHIAN HARDWOOD FORESTS

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Abstract.—Decomposing stumps are prevalent in managed forest ecosystems although the impact of these microsites on nutrient retention and cycling is relatively unknown. In this study, stumps were defined as the aboveground and belowground (i.e., root system) left over from previous harvests. The objective of this study was to quantify the total soil volume occupied by stumps and compare total soil carbon (C) and nitrogen (N) between the bulk soil and soil directly influenced by decomposing stumps. Six randomly established 10 m x 10 m plots were evaluated. These sites were located in mature hardwood stands on the Jefferson National Forest in the Ridge and Valley Physiographic region of southwest Virginia. Approximately 26 percent and 36 percent of the total soil nitrogen and carbon, respectively, were estimated to be contained within the soil influenced by decomposing stumps. These results suggest that decomposing stumps are influential in forest nutrient cycling.

INTRODUCTION

Soil nutrient availability is variable both temporally and spatially (Nye and Tinker 1977). Plants have evolved to maximize nutrient acquisition by exploiting soil heterogeneity via changes in root proliferation, uptake kinetics and mycorrhizal infections (Drew 1975, Drew and Saker 1975, Fitter 1994, Gile and Carrero 1917, Jackson and others 1990, Robinson 1994). There is tremendous inter- and intra-species variation in root growth as nutrients become available either periodically during the growing season or as roots randomly encounter nutrient-rich microsites. Forest soils are particularly heterogeneous for several reasons. First, the effect of tree species on soil nutrient cycling and soil genesis and the mutual effect of soils on tree development and species composition cause both coarse- and fine-scale heterogeneity (Stone 1975). These changes are difficult to quantify because forests are dynamic entities, often requiring centuries or millennia to produce profound changes on the underlying soil. Secondly, land use history and the anthropogenic impacts (e.g., logging and agriculture) on soil often accelerate changes in soil fertility and soil structure. Lastly, actively managed forests typically occur on land unsuitable for agriculture because of steep slopes, high soil stoniness, and low inherent soil fertility due to underlying parent material. These three factors—species composition, land use history, and various landscape attributes—all contribute to forest soil heterogeneity.

A particular source of heterogeneity that has received little attention is the impact of decomposing stumps have on nutrient storage and availability (Van Lear and others 2000), fine root growth, and microbial biomass. Old root channels, for example, have been known to increase spatial heterogeneity in the soil, which provides optimum conditions for root growth due to: 1) increased transfer of water, nutrients, gases, and humus (Kostler and Bruchner 1968); 2) greater aeration and moisture relations (Lutz and Chandler 1947, Van Rees 1984); and 3) decreased soil strength, which can be extremely important in high density and compacted soils (Bennie 1983). Similarly, it would be expected that decomposing tree stumps and their associated root systems also provide a microsite rich in available nutrients and organic

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matter. Decomposing stumps essentially create an extension of the nutrient-rich O- and A-horizons when compared to the surrounding bulk soil.

The lack of information regarding the impact of stumps on nutrient cycling illustrates the need for more detailed research on these relic features. As most stumps are often remnants of past logging operations, a clearer understanding of the contribution and release of nutrients over time could reduce the use of soil amendments (i.e., fertilizer use) by forest managers as stump frequency increases. Therefore, the objectives of this study were twofold: 1) determine the proportion of total soil volume occupied by remnant stumps in a second-growth hardwood forest; and 2) compare total soil C and total soil N between areas directly under decomposing stumps and the bulk soil (A- and B-horizons).

STUDY AREA

This study was installed on the Jefferson National Forest in the Ridge and Valley physiographic region approximately 8 km west of Blacksburg, VA, in Montgomery County (37°17′38″ N, 80°27′27″ W). The elevation is approximately 670 m and the average annual precipitation is approximately 101.5 cm. Average annual temperature is 10.8 °C, ranging from 0.3 °C in the winter to 20.7 °C in the summer. The forest cover type is predominately white oak (*Quercus alba* L.), black oak (*Q. velutina* Lamb.), and scarlet oak (*Q. coccinea* Muenchh.) with red maple (*Acer rubrum* L.) and several species of hickory (*Carya* sp.) as associates in this mixed hardwood community. Forest soils in this region are often derived from a combination of sandstone and/or shale in residuum or colluvial parent materials. The soil in this study is classified as a Clymer soil series (coarse-loamy, siliceous, active, mesic typic hapludult) with an average soil depth of 68 cm. The forests are second-growth forests approximately 80 to 100 years in age as a product of extensive clearcutting and high-grading practices during the late 19th and early 20th centuries.

MATERIALS AND METHODS

Experimental Design

Six, 10 m x 10 m plots were randomly established on soils classified as the Clymer series. At each plot, the entire forest floor (i.e., leaf litter) was removed so that all decomposing stumps could be easily identified. For this experiment, stumps were classified as the aboveground and belowground (i.e., associated rooting system) portions of the tree remaining after previous harvests or as a result of stochastic events (e.g., disease, insects, etc.) that resulted in a standing stump-like feature. Windthrow or tip-up mounds were not evaluated. At each plot, one bulk soil sample by horizon (i.e., A- and B-horizons) was taken for every decomposing stump identified. The location for each bulk soil sample was determined by dividing each 10 m x 10 m plot into 1 m x 1 m cells labeled 1 to 100. An appropriate number of bulk soil sample locations were randomly selected from this pool based on the number of decomposing stumps identified for a given plot. If a tree, decomposing stump, or other feature resided within a randomly chosen cell then another cell was selected as a replacement. Of primary interest regarding the decomposing stumps is the soil directly underneath, which has been churned and modified by root growth and turnover.

Estimation of Soil Volume Influenced by Decomposing Stumps

A soil push-tube sampling device was used to estimate the extent of soil material influenced by decomposing stumps. Four depth measurements were collected at each cardinal direction to determine the relative extent of soil influenced by the associated root system. Pressure was applied to drive the soil sampler through the stump as deep as possible. If the stump was not highly decomposed to warrant the use of the push-tube through its center, then the sampler was angled at the edge of the stump so that it could be driven into the soil directly under the center of the stump. Qualitative attributes such as changes in soil color were used to determine the extent of the soil influenced by each stump's decomposing root system. In conjunction with the depth measurements, two cross-sectional diameter measurements of the stump were collected. Together, these two measurements, diameter and depth, were inserted into an equation for an elliptical cone which represented the assumed shape of the underlying root system:

$$V = \frac{\pi D^2 S_D}{6} \quad (1)$$

where

V = volume of soil influenced by a decomposing stump
D = mean diameter of a decomposing stump
S_D = average depth or extent of soil influenced by a decomposing stump

We recognize that all soil is somewhat influenced by roots. In this study only the areas highly affected by decomposing stumps were considered (i.e., major coarse root portion). As the coarse roots decompose, a pronounced coloring of the soil occurs, allowing for an easily identifiable boundary between the decomposing stump and the adjacent bulk soil.

Soil Sampling and Analysis

Bulk Density Determination

A soil bulk density corer was used to obtain samples for determining bulk density (D_b) for each sampling location (n = 2). For the bulk soil, bulk density samples were taken by horizon. All samples were oven dried at 105 °C for 48 hrs and separated into the >2-mm and <2-mm fractions using a 2-mm sieve.

Total C and N Determination

The combustion method was used to determine the concentration of N and C present in the fine-earth fraction (<2-mm) for the bulk soil and decomposing stump samples (Nelson and Sommers 1982) using an Elementar CHNS analyzer (Elementar, Hanau, Germany). Total N and C were expressed in kilograms (kg) and megagrams (Mg) per hectare as follows for the bulk soil:

$$\text{Total N (kg}\bullet\text{ha}^{-1}\text{) or C (Mg}\bullet\text{ha}^{-1}\text{)} = D_b(g \bullet cm^{-3}) * depth(cm) * [\%N\_or\_\%C] * 1000 \quad (2)$$

Equation 2 is the traditional method for converting concentrations of C and N to a kilogram per hectare basis, where an average horizon thickness (i.e., depth) is used in conjunction with measured soil physical and chemical data. On the other hand, extrapolating C and N concentration data from decomposing stumps required slight modifications because stumps are three-dimensional, have irregular boundaries, and occur intermittently across the landscape. Consequently, total stump volume is used along with bulk density (D_b) and C and N concentration data on a per plot basis (100 m^2) and then extrapolated to a per hectare basis (10,000 m^2). Since carbon totals were extremely high, values were converted to a megagram per hectare basis.

In addition to the examination of total C and N between the bulk soil and soil beneath decomposing stumps, research goals also include examining differences in major macronutrients such as available Mg^{2+}, Ca^{2+}, and K^+, inorganic species of N (NO_3^- and NH_4^+), fine root dynamics, and microbially derived N and

Table 1.— Bulk density and percent carbon and nitrogen soil physical and chemical data for the A- and B-horizons of the bulk soil and decomposing stumps

Soil Sampling Area	Bulk Density (g cm^{-3})		% Carbon		% Nitrogen	
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
A-Horizon	1.20A	0.26	2.33B	0.9	0.113B	0.014
B-Horizon	1.55A	0.13	2.01B	0.85	0.116B	0.024
Decomposing Stumps	0.63B	0.21	16.4A	0.15	0.534A	0.095

*Significant differences denoted by different capital letters using Tukey's LSD (α = 0.05) for each physical and chemical measurement(s).

Table 2.—Total soil volume of A- and B-horizons and decomposing stumps as well as the proportion of total soil volume, percent C, and percent N comprised by the measured soil sampling areas

Soil Sampling Area	Soil Volume (m^3 ha^{-1})	Total Percent Contribution		
		Soil Volume	Carbon	Nitrogen
A-Horizon	1125	14%	6%	10%
B-Horizon	7100	85%	57%	63%
Decomposing Stumps	103	1%	37%	27%

C. Furthermore, the impact of these stumps on poor versus high-quality sites characterized by different soil types will also be examined.

Statistical Analysis

Paired t-test was used to test for differences in total C and N between the bulk soil and decomposing stumps using an alpha-level of 0.05. Tukey's LSD procedure was also used as a multiple comparisons procedure to test for differences between percent N, percent C, and bulk density for individual horizons within the bulk soil and soil influenced by decomposing stumps using an alpha of 0.05 as well. SAS JMP version 6.0.2 statistical software (SAS Institute Inc., Cary, NC, 2006) was used to analyze these data.

RESULTS

Soil physical and chemical data varied between the bulk soil A- and B-horizons and the decomposing stumps; soil percent C and N were higher for the decomposing stumps, while bulk density was less (Table 1). Only 1.2 percent of the total soil volume was occupied by decomposing stumps (Table 2). However, decomposing stumps account for approximately 36.5 and 27.0 percent of the total soil C and N analyzed, respectively (Table 2).

When total megagrams C and total kilograms of N per hectare were examined, two different C and N pools were estimated. One pool included the total C and N found collectively in the A- and B-horizons only, and the second pool included the total C and N found in both the stumps and the A- and B-horizons, respectively (Figs. 1 and 2). When stumps were included in C and N estimations, total soil volumes for the A- and B-horizons were adjusted based on the soil volume influenced by stumps using Eq. [1].

Total soil C estimates for the A- and B-horizons were approximately 281 megagrams of C per hectare, where the A-horizon contained 31 Mg of C and the B-horizon 250 Mg of C per hectare, respectively

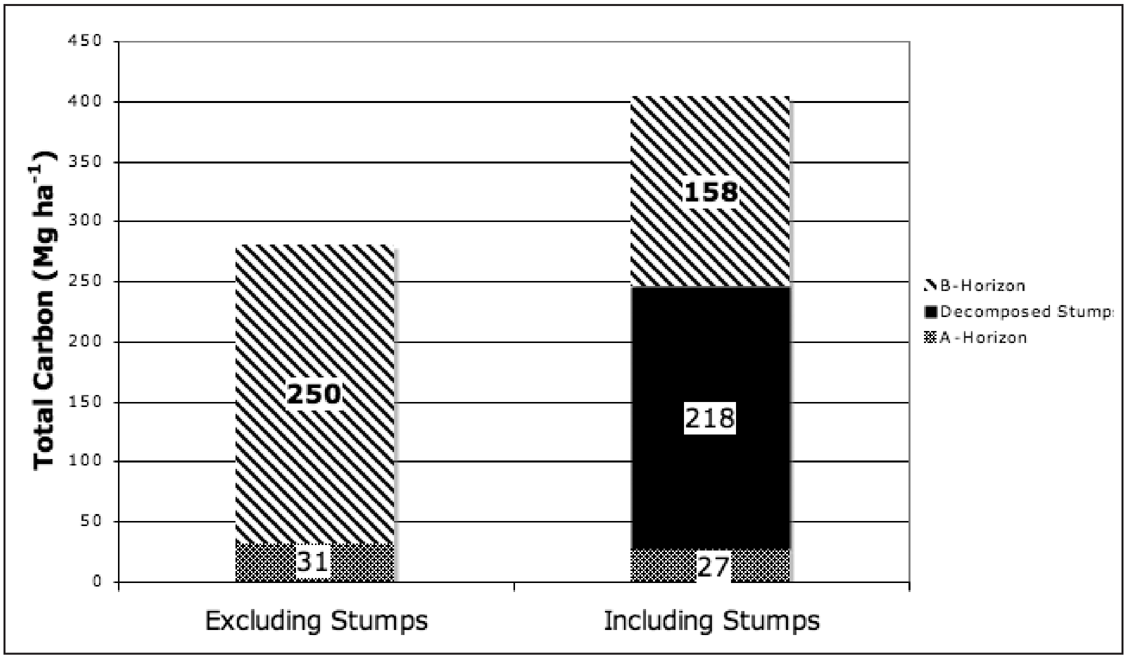

Figure 1.—Total soil carbon pools for estimates excluding and including decomposing stumps for soils on the Jefferson National Forest, Blacksburg, VA.

(Fig. 1). Conversely, when soil volume was adjusted to include the stumps in addition to the A- and B-horizons, total soil C was 403 Mg per hectare (Fig. 1). When examined individually, the A-horizon contained 27 Mg of C and the B-horizon 158 Mg of C. Stumps contained 218 Mg of C per hectare, which was significantly greater than C values that excluded soil influenced by decomposing stumps ($p = 0.03$).

For soil N estimates the A- and B-horizons contained approximately 13,622 kg of N per hectare with the A-horizon containing 1795 kg of N and the B-horizon 11,827 kg of N per hectare (Fig. 2). On the other hand, when soil volume was adjusted to include stumps in addition to the A- and B-horizons total soil N was 16,897 kg of N per hectare (Fig. 2). When examined individually, the A-horizon contained 1570 kg of N, the B-horizon 10,343 kg of N. Stumps contained 4984 kg of N per hectare, which was also significantly more than estimates that excluded soil influenced by decomposing stumps ($p = 0.03$).

DISCUSSION

Decomposing stumps accounted for 36.5 percent of the total soil C (Table 2), which suggests that global C stocks for forested ecosystems may be significantly underestimated if these relic features are not included. The decomposition stage of these stumps could also have an effect on the amount of labile C. For example, stumps that have undergone very little decomposition will likely have higher C:N ratios and lower potential N mineralization rates, whereas older more heavily decomposed stumps would likely have lower C:N and thus higher N mineralization rates and N availability (Van Lear and others 2000). Decomposing stumps accounted for 27.0 percent (4984 kg ha^1) of the total N (Table 2 and Fig. 2) found within the A- and B-horizons, which is a substantial amount of N when this nutrient often limits productivity in many forested ecosystems. These findings show that significant amounts of N and C are present in stumps. Perhaps other major nutrients such as Mg, Ca, P and K may also be contained within these stumps (Van Lear and others 2000).

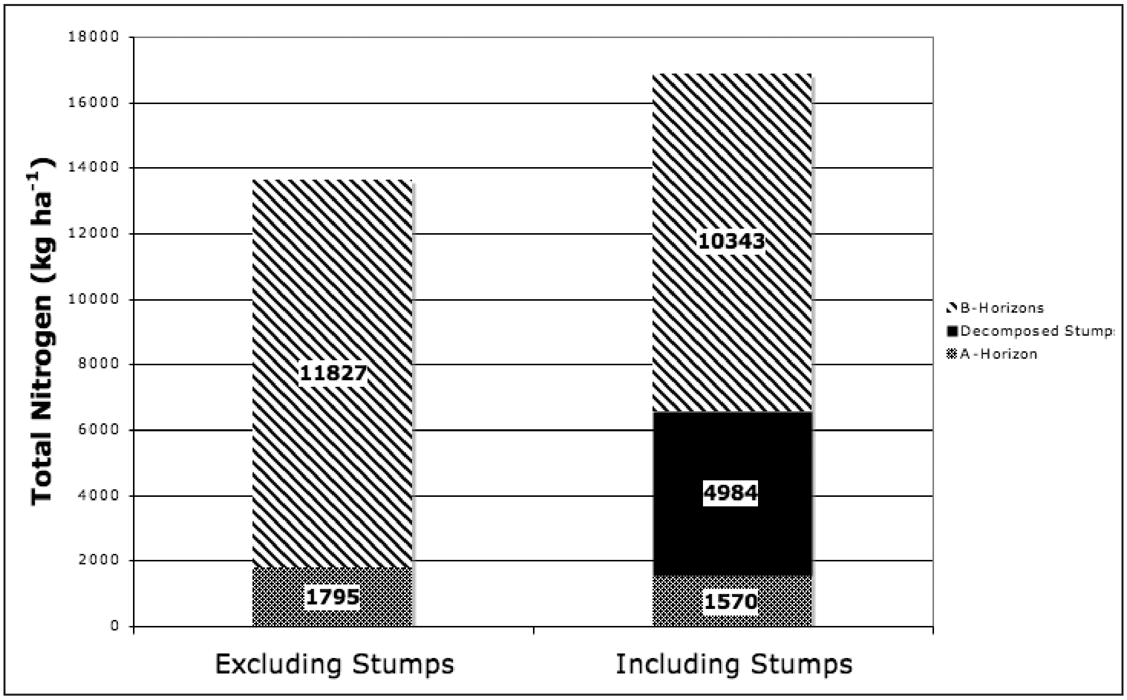

Figure 2.—Total soil nitrogen pools for estimates excluding and including decomposing stumps for soils on the Jefferson National Forest, Blacksburg, VA.

Van Lear and others (2000) examined the impacts decaying stumps have on site productivity of loblolly pine (*Pinus taeda* L.). This particular study showed that loblolly pine productivity and rooting density increased for trees in closer proximity to old decaying stumps. Elemental concentrations of C (C), N, Mg, Ca, and P were seven to 40 times higher in decomposing root systems/stumps than in the root/soil interface and soil matrix, respectively. Tree roots often extend to lengths two to seven times greater than the height of the tree; however, the area directly surrounding the tree stump provides the majority of beneficial attributes associated with decomposition processes (Van Lear and others 2000). In addition, these rich microsites provide a habitat ideal for microorganisms. In the early phases of decomposition, there is an increase in C which results in high C:N ratios and lower nutrient availability; however, as decomposition progresses and the C:N ratio declines, nutrient availability increases due to rapid mineralization (Van Lear and others 2000). This pattern emphasizes the importance of examining decomposing stumps following harvest or mortality.

Decomposing stumps represent microsites rich in nutrients. Plants in close proximity to these stumps may have a competitive advantage over other plant species that are farther away (Van Lear and others 2000). Plant communities adapted to sites with either high or low nutrient availability may benefit differently from decomposing stumps. Plants occurring on poor quality sites are often adapted to taking advantages of short pulses of increased resource availability (e.g., decomposing stumps), but are not as adapted to exploiting increases in nutrient availability when supplied for long periods (Campbell and Grime 1989, Crick and Grime 1987, Grime and others 1986). This adaptation to heterogeneous environments for plants occurring on low quality sites can be attributed to: 1) the overall low nutrient demand to obtain optimal growth; and 2) the relatively slow root turnover rate and lower risk of nutrient loss (Crick and Grime 1987). On the contrary, plants adapted to fertile environments are more responsive to a sustained supply of nutrients (i.e., relatively homogenous soil environments) and often have higher tissue turnover, dry mass allocation, and nutrient absorption rates than plants occurring on infertile sites (Campbell and Grime 1989), but these values are lower when the plants are grown on infertile sites. Therefore, decomposing stumps may be more important on sites with lower site quality where plants are adapted to taking advantage of heterogeneous supplies of nutrients than plants found on high quality sites.

CONCLUSIONS

Tree stumps and the underlying root systems can contain as much biomass as the overstory portion of trees. These results initially suggest that decomposing stumps are influential in forest nutrient cycling and that a stratified sampling scheme versus conventional random sampling may help forest scientists better understand the role of soil heterogeneity. Thus, more comprehensive research investigating the influence of stumps is required.

ACKNOWLEDGMENTS

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HUMAN DIMENSIONS AND ECONOMICS

USER GROUP ATTITUDES TOWARD FOREST MANAGEMENT TREATMENTS ON THE SHAWNEE NATIONAL FOREST: APPLICATION OF A PHOTO-EVALUATION TECHNIQUE

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Abstract.—Diverse public opinions, competing management goals, and polarized interest groups combine with problems of scale to create a complex management arena for managers in the Central Hardwood Forest region. A mixed-methods approach that incorporated quantitative analysis of data from a photo evaluation-attitude scale survey instrument was used to assess attitudes toward forest management practices in southern Illinois. Stakeholder groups that use the Shawnee National Forest (SNF) rated color photographs of forest management treatments. Responses to three targeted management themes—trails, harvesting, and fire—were elicited by photographs paired with a semantic differential attitude measurement scale. Each theme was represented by three photographs depicting a management treatment stage. Follow-up interviews were used to acquire a greater understanding of participant knowledge level of management practices as well as beliefs underlying the photo evaluations. Study findings suggest that this survey method can be a useful tool for measuring attitudes so as to avoid conflict or litigation like that of the SNF management plan process in recent decades.

INTRODUCTION AND OBJECTIVES

Literature related to forestry and natural resources partnership building and conflict resolution seeks to understand how problems originate (McCool and Guthrie 2001, Lachapelle and others 2003, Nie 2003). Drivers of resource-based conflicts can include: resource scarcity, scientific ambiguity, policy design shortcomings, ineffective communication, lack of trust, and different valuations of place. Public land managers must integrate public voices into decision-making processes both to minimize conflict and to be in accordance with public statutes. J. Clarence Davies, Director of the Center for Risk Management in Washington D.C., states that "participatory methods [have been] institutionalized in environmental law (1998, p. 2)". He goes on to note, however, that participatory methods have not always been effective. In many instances, attempts to foster public involvement in natural resource decisionmaking has not led to true collaboration (Smith and McDonough 2001). New strategies are needed to identify and integrate diverse perspectives about forest management practices earlier in decision-making processes (Reynolds 2002). This paper presents findings from a pilot study of a photo-evaluation technique designed to quantitatively assess and to qualitatively validate different attitudes and values held by stakeholder groups of the Shawnee National Forest (SNF) toward forest management practices.

STUDY AREA

The SNF, situated south of Illinois' glaciated, agricultural central portion, dominates the rolling landscape of southern part of the state. The 277,506-acre forest encompasses six Illinois Natural Divisions: Coastal Plain, Lower Mississippi River Bottom Lands, Ozarks, Shawnee Hills, Southern Till Plain, and the Wabash Border Division (Illinois Department of Natural Resources 2007). Unlike the remainder of Illinois, this region is characterized by rocky terrain, rolling hills, limestone cliffs, and sandstone bluffs. The climate of

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southernmost Illinois supports ecosystems unique to the state such as an internationally significant wetland system. Federal holdings that comprise the SNF were acquired partially through donations to the USDA Forest Service with the balance purchased through authority granted in the Weeks Act of 1911 (Welch and Evans 2003, USDA Forest Service 2007). Due to this acquisition history, the national forest land is interspersed with private, municipal, state, and other federal lands. Although the SNF now contains some of the largest forest tracts in the state, it is one of the most fragmented units in the National Forest System.

Efforts to involve the public in SNF decisionmaking have tended to focus on local concerns. However, southern Illinois residents represent only one segment of those with a potential stake in forest management. The Shawnee National Forest lies within a half-day's drive of Memphis, TN; Louisville, KY; Indianapolis, IN; Chicago, IL; and St. Louis, MO. This location places the SNF within 350 miles of more than 45 million people, roughly 17 percent of the U.S. population (USDA Forest Service 2007). These urban areas provide a large, diverse population of users that seek out the SNF for its unique cultural and natural heritage and that greatly add to existing use by local communities (Welch and Evans 2003).

Lack of support for timber harvesting on the SNF by local environmental advocacy groups spiraled into a contentious issue in the 1990s and led to these groups seeking legal recourse. Decisions handed down by regional federal courts (Sierra Club et al. v. USDA et al. 1996) essentially halted most timber management on federal property in southern Illinois (Welch and Evans 2003). Reynolds (2002, p. 245) suggests that legal gridlocks of this nature could be avoided if the Forest Service substantially improved its traditional decisionmaking practices by incorporating public concerns more effectively. Today, a new SNF management plan has the potential to usher in a new period of communication and collaboration in southern Illinois.

Previous Research on Shawnee National Forest

Recent literature related to the SNF and its associated ecosystems has focused primarily on natural processes, specifically hardwood forest regeneration and application of prescribed fire (Groninger and others 2005, Ozier and others 2006, Ruffner and Groninger 2006). A notable exception was a 2003 Indiana University social assessment of SNF history, local community sociodemographics, and stakeholder viewpoints. This study (Welch and Evans 2003) addressed regional poverty, management conflicts from the 1990s, and public and stakeholder views of forest management. The study attempted to provide an in-depth understanding of the expectations and values of local residents. Many participants held complex views about forest management practices and expressed concerns about potential impacts on forest vegetation and wildlife. Welch and Evans (2003) concluded that producing a forest management plan that stakeholders can accept depends upon clarifying which management issues are most important to stakeholders prior to plan implementation. The photo-evaluation tool under development and presented in this paper is an attempt to quantify and clarify where different attitudes and values exist between managers and other forest stakeholders.

INTEGRATING PUBLIC INPUT

According to Burger (2000), management of ecosystems is a social process. Management of a complex forest ecosystem at the landscape level requires collaboration and open communication between agencies and all relevant stakeholder groups. Maintaining communication can be difficult if individuals and groups cannot find common ground upon which to build a dialogue. Social science tools can be applied to open channels of communication and to help managers and the public identify and articulate areas not only of disagreement but also of agreement. The objective of the present study is to develop a photo-evaluation

Acceptable	___:___:___:___:___:___:___	Unacceptable
Not-sustainable	___:___:___:___:___:___:___	Sustainable
Impacted	___:___:___:___:___:___:___	Pristine
Constructive	___:___:___:___:___:___:___	Destructive
Environmentally Friendly	___:___:___:___:___:___:___	Environmentally Degrading
Unpleasant	___:___:___:___:___:___:___	Pleasant

Figure 1—Prescribed fire forest treatment photograph paired with semantic differential scale.

survey protocol to measure attitudes toward specific forest management treatments. The goal is to develop a practical tool that is easy to tailor to unique management settings while also being cost effective in production and distribution.

Attitude Measurement

The present study combines two types of attitude measures: rating scales and photographic evaluation. Spector (1992) points out that summated rating scales tend to have strong reliability and validity, are generally easy to develop, and are easy to administer. Most important, their results indicate strength of feeling (Spector 1992). Summated rating scales differ from yes/no questions in that they ask participants to respond to a range of values, generally presented as five to seven choices arranged from "strongly agree" to "strongly disagree". The semantic differential scale (Henerson and others 1987) combines a summated rating scale with bipolar adjective pairs to elicit attitudes on a given topic or "attitude object" (Fig. 1). Using a semantic differential scale maximizes the benefits of summated rating scales by "summating the summations", adding to scale reliability. Presenting the subject with multiple adjective pairs also helps to identify which stimulus is eliciting a positive or negative attitude. Our survey instrument presents subjects with color photographs treated as attitude objects that are paired with a semantic differential scale.

Photography as a Research Tool

Recent developments in photography (e.g., disposable cameras and digital photography) have made it a viable research tool. A prominent research topic in recent visual studies is landscape appreciation through photo elicitation (Froment and Domon 2005). Stedman and others (2004) argue that photographs can be used to express meaning in a variety of natural resource settings and refer to an earlier work by Rose (2001), who wrote that photographs offer evidence of historically, culturally, and socially specific ways of seeing the world. Goin (2001) further suggests the need for researchers to move beyond considering photographs merely as support for data, but rather as expressions of ideas themselves.

Reliability and Validity

Netemeyer and others (2003) write that validity cannot be assessed directly, but rather must be determined by assessing results and comparing them against expected outcomes or existing known measures. Our protocol uses follow-up interviews and focus group discussions to assess the validity of attitude rating outcomes. Semi-structured interviews and focus groups will evaluate whether subjects actually responded to the management treatments portrayed in the survey photographs or whether their responses were based on outside influences. Reliability of our photo-evaluation attitude rating scale will be estimated through an internal consistency procedure with the Cronbach's alpha coefficient.

METHODS

Three stakeholder groups were identified through study of past national and local conflicts related to forest management issues: local environmental activists (n=11), national forest trail users (n=10), and U.S. Forest Service staff (n=10). Although any one individual may associate with multiple groups, group membership was determined by organizational rosters and mailing lists. An open-ended survey question asked with which stakeholder group the subject primarily identified.

Phase-one data collection occurred during the 2006-2007 academic year. Surveys were administered in person with the lead author, a graduate research assistant, present. Each subject (n=31) was shown nine photographs depicting three different applications of forest management practices: trails, fire, and harvesting. These applications were chosen because they represented three major management actions on the SNF. Each application was represented by three scenes depicting different stages, or impact levels, of the management treatments. Color-printed photographs were positioned above a semantic differential scale on the survey form. Participants were asked to consider each photograph carefully and then respond to bipolar terms on the attitude scale (Fig. 1).

Follow-up interviews were conducted with four respondents, randomly selected from each of the three stake-holder groups, to discuss feelings and beliefs underlying the attitudes expressed in the context of place attachment. Interview transcripts were coded and analyzed with qualitative research techniques (Strauss and Corbin 2000). In phase two of this ongoing study, these follow-up interviews will be used to assess scale validity.

Quantitative analysis involved calculating a summated attitude rating score for each management treatment photograph-semantic differential combination and then comparing ratings across stakeholder groups using one-way analysis of variance (ANOVA). Our research hypothesis predicts that different SNF stakeholder groups will hold varying attitudes toward management treatments.

Table 1.—Means and range of attitude rating scores for all groups based on treatment photograph theme (n = 31)

Treatment	Mean	Minimum	Maximum
Fire	4.64	-7	16
Harvest	5.78	-8.33	16.67
Trails	0.10	-13.33	13.67

Table 2.—ANOVA results of group differences in attitude rating scores assigned to treatment themes

		df	F	Sig.
Mean Fire Score	Between Groups	2	10.89	0.001
	Within Groups	29		
	Total	31		
Mean Harvest Score	Between Groups	2	3.72	0.036
	Within Groups	29		
	Total	31		
Mean Trails Score	Between Groups	2	1.58	0.223
	Within Groups	29		
	Total	31		

Study limitations can be posed as questions. First, are the photographs accurately eliciting attitudes related to the depicted scenes of forest management; and second, is the scale sensitive to different attitudes held by SNF stakeholder groups? Another limitation of the survey instrument is its length, which presents potential obstacles to larger-scale application. In contrast to large mail-based surveys that often experience low response rates, this pilot study had a response rate greater than 99 percent.

RESULTS

Results indicated a wide range of mean attitude rating scores across the three participating SNF stakeholder groups (Table 1). In addition to the variation in responses to each treatment theme (Table 2), the responses elicited by individual photographs also varied widely (Table 3). The variation in mean attitude rating scores and the variation between photographs and between groups demonstrated that this protocol is a viable method to measure stakeholder attitudes toward forest management. The reliability test yielded an alpha value of 0.78, indicating satisfactory scale reliability. A larger sample size is planned for phase two of this continuing study.

Attitude ratings were analyzed in two ways: first by treating each set of related management treatment photographs as a themed series with a single attitude rating (Table 2); and second, by considering the attitude rating assigned to each individual photograph (Table 3). This process is important because each stage of the pictured management treatments can look very different and attitudes elicited by one treatment may change, based on level of impact or time elapsed since disturbance. Analysis (ANOVA) of management theme data shows SNF stakeholder groups exhibit significant differences in attitudes toward scenes depicting the effects of both fire and harvest. Differences in attitudes toward harvest treatments were expected because harvesting practices on the SNF were the major source of stakeholder conflicts throughout the 1990s.

Table 3.—ANOVA results of group differences in attitude rating scores assigned to individual photographs

Photograph Content		df	Sig.
Harvest 14 years post treatment	Between Groups	2	0.243
Fire at time of treatment	Between Groups	2	0.001
Harvest 100+ years post treatment	Between Groups	2	0.415
New backcountry trail	Between Groups	2	0.352
Harvest 1 year post treatment	Between Groups	2	0.006
Degraded backcountry trail	Between Groups	2	0.077
Fire 5 years post treatment	Between Groups	2	0.022
Hardened trail surface	Between Groups	2	0.037
Fire 1 day post treatment	Between Groups	2	0.030

Variation in responses to photographs grouped as themed management series prompted analysis of each photo separately (Table 3). Of the nine treatment photographs, five elicited significantly different responses between stakeholder groups. In support of the grouped theme analysis, all three individual fire photographs elicited significantly different responses. A photograph depicting a clearcut the same year as the treatment and a photograph of a hardened trail surface, also elicited significant differences in attitudes. Further post-hoc analysis will address between-group differences.

DISCUSSION

Preliminary study findings confirm the potential of photo-evaluation techniques to assess attitudes toward forest management practices. The various SNF user groups surveyed to date were able to distinguish among different management treatments as well as different treatment stages or levels of impact. Interpretation of study findings can clearly indicate where important areas of agreement or disagreement exist between managers and other stakeholder groups. For example, although photos of timber harvest elicited significant differences when treated as a series, the only individual harvest photo to do so was that depicting a recent harvest. All stakeholder groups differed significantly on all photos of prescribed fire, both as a themed series and also when considered individually. These preliminary findings suggest that this survey method can identify socially unacceptable management practices and help managers respond to public concerns earlier in the decision-making process (Reynolds 2002). Future directions for this research project will involve a replication study with a larger sample size, assessment of the effect explanatory photo captions have on attitude ratings, and an exploration of a web-based survey version to facilitate larger-scale survey distribution.

Contemporary natural resource conflicts often revolve around stakeholder values, values that typically differ from those of managers. One solution to such "messy" problems would be adoption of a management style that better incorporates the values of all interested parties—fully—from the beginning. As previously stated, this approach can succeed only if dialogue is encouraged. The attitude measurement tool we are developing is designed to help managers identify value commonalities among stakeholder groups. The tool incorporates a questionnaire form that is relatively quick to modify and easy for participants to complete. Ultimately, creating new methods to solicit and document public input can facilitate an atmosphere of proactive response rather than mere reaction to value-based conflicts on the SNF and elsewhere.

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ESTIMATING WILLINGNESS TO PAY FOR PROTECTION OF EASTERN BLACK WALNUT FROM DEER DAMAGE

Larry D. Godsey and John P. Dwyer[1]

Abstract.—For many landowners willing to plant trees, one of the biggest establishment and maintenance costs is protecting those young trees from deer browse damage. In some cases, the method of protection used can cost two to three times as much as the cost of planting. Deer damage such as nipping off terminal buds and buck rub penetrating the bark and cambial tissue can kill young trees or cause substantial degradation in future log quality and value. An estimate of landowners' willingness to pay for damage abatement, or willingness to accept deer damage can indicate the economic impact that deer populations have on timber investment. Returns to investment are dramatically reduced when excessive costs for deer abatement are compounded to a future harvest. Three black walnut plantations are analyzed to determine the amount of deer damage present, and the costs of deer protection methods. Two methods of estimating willingness-to-pay are used. Hypothetical levels of deer damage are used to calculate estimated costs of protection methods. These costs of protection are then discounted to a present value to compare the reduction in present value caused by increased levels of deer protection. A second method, the damage cost method, uses net present value analysis to determine the difference in net present value of a plantation with no damage and one with maximum deer damage. This difference in net present value reflects the maximum willingness to pay for deer protection. Several scenarios are analyzed to estimate a landowner's willingness to pay for deer protection or willingness to accept deer damage. The results indicate that the willingness to pay for abatement on a plantation of black walnut that is established for nut production is higher than on a plantation established for timber production.

INTRODUCTION

In Missouri, one of the biggest expenses incurred when establishing a plantation is protection of trees from white-tailed deer (*Odocoileus virginianus*). In some cases the cost of protecting young seedlings can be as much as 10 times the cost of the seedling itself. There are numerous ways of protecting trees from deer damage, such as fencing, scare devices, deer repellant, and various other methods (Pierce and Wiggers 1997, Scott and Townsend 1985). However, the cost and the effectiveness of each of these methods can vary tremendously. One particular study of wildlife damage on the apple (*Malus* spp.) industry in the Hudson Valley region conducted in 1986 estimated that wildlife damage cost each grower an average of $12,500 per year, with almost half of this cost in wildlife control measures (Phillips and others 1987). As deer herds increase, the probability of deer damage on orchards and other plantations increases. One question that many landowners ask is "What is the best method for preventing deer damage on trees?", and "Is it worth my investment or time to do this?" The answer to this question depends on the landowner's goals and objectives for that particular plantation, the type of tree species being planted, and the risk of deer damage to the trees.

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OBJECTIVES

The focus of this study is on the cost of deer damage on eastern black walnut (*Juglans nigra* L.) in Missouri. Much emphasis has been placed on the production of black walnut for potential income from both nuts and timber. White-tailed deer (*Odocoileus virginianus*) can cause serious damage to young black walnut trees by nipping terminal buds and by rubbing the bark and subsequently damaging cambial tissue of juvenile trees. This threat presents a problem to growers of black walnuts who are interested in producing a high-value timber crop. Nipping the terminal bud from the terminal leader and lateral branches of a black walnut can postpone the financial maturity of the tree 8 to 10 years and in some cases eliminate any possibility that the tree will produce a veneer-quality butt-log. In a worst-case scenario, deer browsing can actually kill a young tree. Deer rub can be almost as devastating to a young plantation because bark is often stripped from the tree, exposing cambial tissue. Wounds caused by deer rub can cause log and lumber value degradation or become an entry point for diseases. For growers who are interested in a nut crop, deer browsing can set nut production back by as much as 10 years and destroy high-value grafted stock. Although deer rub has less impact on nut production, it can create a wound on a tree that will allow entry points for disease and insect pathogens.

This study looked at existing stands of eastern black walnut trees at various ages to determine the probability and severity of deer damage. These estimates were then used to reflect the potential damage without deer protection. The objective of this paper was to calculate expected net present value of the timber stand with and without deer damage in order to estimate a landowner's imputed willingness to pay for deer protection for young trees, or in most cases, the imputed willingness to accept deer damage. The economic concept of willingness-to-pay should not be confused with the idea that the landowner is actually required to make a payment. The idea of willingness-to-pay and willingness-to-accept simply reflects the level of consumer or producer surplus that can be exchanged to reach a Pareto optimal level where the individual is no better or worse off (Just and others 2004). For this paper, willingness-to-pay and willingness-to-accept are estimations of the potential economic surplus that could be used to prevent deer damage, whether paid or accepted. It is estimated that willingness-to-pay will vary depending on the age and purpose for growing the trees. One expected outcome from this paper is to provide a range of economically feasible costs for landowners growing black walnut for nuts or timber.

STUDY AREAS

Several black walnut plantations of various ages were located in central Missouri as study sites. Site A is located approximately 15 miles east of Columbia, MO, in Boone County. The trees on site A are between the ages of 5 and 15 years old and planted in east-west rows. Site A has two distinct stands. Stand 1 consisted of 15-year-old trees. Stand 2 consisted of trees ranging in age from 5 to 10 years old. Site A had been managed with moderate pruning and weed control. The landowner's objective for growing the trees is for future timber income. None of the trees on Site A had been protected from deer damage.

Site B is located approximately 80 miles west of Columbia, MO, in Carroll County. This site consisted of 7 acres of 24-year-old black walnut that had been originally planted at a density of 300 trees per acre. According to the landowner's records, 180 trees had been completely destroyed in the first 5 years of the plantation due to deer damage. The tree rows run north and south and the trees are on 12.0- x 12.0-ft. spacing. The trees on this site are being grown for future timber income and have been managed with pruning and occasional weed control. Similar to Site A, none of the trees on this site have been protected from deer; however, the site is regularly hunted.

Site C is located about 2 miles west of Columbia, MO. It consists of numerous stands of trees varying in age from 5 to 30+ years of age. It appears that the original spacing on most of the stands is 10.0 x 10.0 ft. Site C had small stands of equal age, and row arrangement varied with the contours of the site. Some stands have rows that run north and south and some stands have rows that run east and west. Most of the younger trees were protected with wire cages and metal T-posts. Older stands were not protected at the time of inspection. Some pruning had been conducted on the stands; however, no weed control was evident. The landowner's goal for planting the trees is for a future timber income.

METHODS

Random samples of 50 trees per stand at sites A and B, and 25 trees per stand at site C were selected by transecting the stand across rows, working from one outside edge to the opposite outside edge. The data collected consisted of diameter at breast height (d.b.h.) in inches measured with a diameter tape; height in feet measured with a Laser Technology, Inc laser hypsometer; and a subjective estimate of value damage caused by deer activity. Estimates were also made regarding trees that had the potential for future veneer quality logs. This estimate was based on form, number of clear faces, visible defects, and branching characteristics. In order to estimate deer damage, a value judgment was made based on the following four criteria:

1. Critical Value Damage. Damage to the tree will cause or has caused the tree to die. Stump sprouting may be evident, but the damage most likely has been fatal (Fig.1, A).
2. Severe Value Damage. Damage to the tree will not be fatal, but the tree has been set back several years and survives through extensive stump sprouting (Fig. 1, B).
3. Moderate Value Damage. Damage to the tree has caused a wound that will take several years to heal over. Value has been degraded (Fig. 1, C).
4. Light Value Damage. Damage to the tree is superficial and will heal over; however, some value may be lost (Fig. 1, D).

It should be noted that there were other causes of damage on the trees including insect damage, frost cracks, mower/equipment damage, and fungal diseases. However, only the damage that was consistent with typical deer browse and rub was considered.

To calculate a landowner's willingness to pay for deer control, equations 1 and 2 were used to estimate the opportunity cost of deer damage:

$$WTP = NPV\text{no damage} - NPV\text{with damage} \qquad \text{(eq. 1)}$$

and,

$$NPV = \sum_{i=0}^{n} \frac{R_i}{(1+r)^i} - \sum_{i=0}^{n} \frac{C_i}{(1+r)^i} \qquad \text{(eq. 2)}$$

where:

R_i = expected revenues in time period i
C_i = expected costs in time period i
r = discount rate
n = total number of time periods

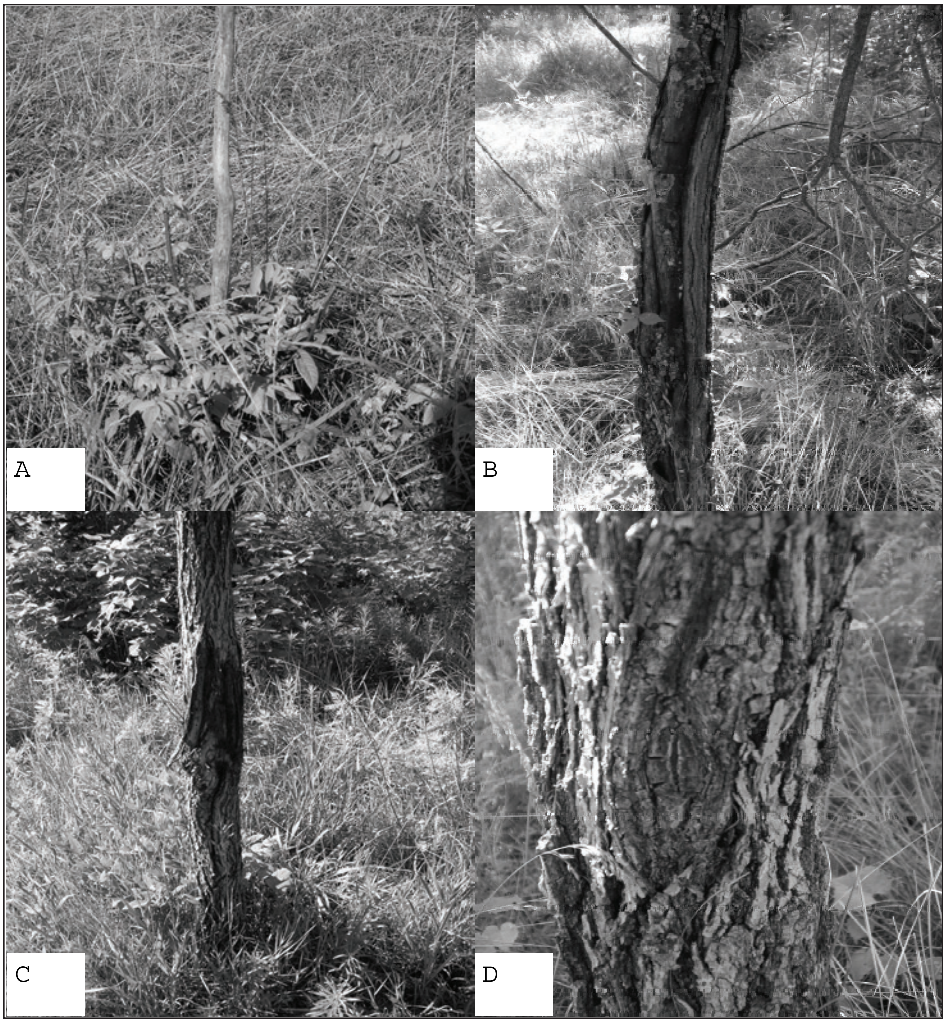

Figure 1.—Examples of trees damaged by deer. Photograph A represents Critical Value Damage; B represents Severe Value Damage; C represents Moderate Value Damage; and D represents Light Value Damage.

The net present value for both timber and nut production was based on the cost and revenues per tree used in the Black Walnut Financial Model (Godsey 2006). Timber prices are based on the stumpage prices reported in the Missouri Timber Price Guide (Missouri Dept. of Conserv. 2007) and other sources:

1. Grade sawlogs - $0.80 per board foot
2. A Veneer - $3.50 per board foot
3. B Veneer - $2.00 per board foot
4. C Veneer - $1.25 per board foot

To capture the loss in value due to deer damage for the timber investment, an estimate of the potential quality of the trees was made based on the site inspections. A weighted average price per board foot was calculated and applied to the model. Table 1 shows how the price per board foot was calculated. For damaged timber trees, the weighting was adjusted to reflect the amount of damage seen on the subject sites and the price per board foot was calculated again using a weighted average value. Also, for the scenarios where damage was present, an additional cost is incorporated for replacement of critically or severely damaged trees, and expected revenues are reduced early in the production years in order to reflect lost

Table 1.—Weighted average prices per board foot for timber with and without damage

	Potential revenue (No Damage)			
Quality	bf	price	Total Value	
Veneer A	981.711	$3.50	$ 3,435.99	
Veneer B	2086.14	$2.00	$ 4,172.27	
Veneer C	613.569	$1.25	$ 766.96	
Sawlog	2454.28	$0.80	$ 1,963.42	
	6135.69		$10,338.64	$1.69/bf
	Potential revenue (With Damage)			
Quality	bf	price	Total Value	
Veneer A	795.787	$3.50	$2,785.25	
Veneer B	2086.14	$2.00	$4,172.27	
Veneer C	613.569	$1.25	$ 766.96	
Sawlog	2640.20	$0.80	$2,112.16	
	6135.69		$9,836.65	$1.60/bf

income due to damaged trees. These costs and income reductions are manually incorporated into the Black Walnut Financial Model.

Other assumptions that were used in the black walnut financial model include a diameter growth rate of 0.3 inch per year, a 50-percent removal of trees at each thinning period; management for one 16-foot log with an average d.b.h. of 24 inches, and thinning is conducted when the crown competition factor reaches 150.

None of the plantations studied were being managed for nut production; therefore, damage estimates from the study sites were applied to a hypothetical black walnut plantation that is being managed for nut production. Costs and revenues for this hypothetical black walnut plantation are based on five existing black walnut plantations that are being managed for nuts. In order to look at the impact on nut production, the following assumptions were used in the black walnut financial model. The cost per grafted seedling was $15, and a nut price based on the average price paid to producers of $0.35 per pound was used. The trees are also thinned when the crown competition factor reached 110; however, since the trees were not managed for timber, they were sold as sawlogs at $0.80 per bf. Only two initial spacing levels were used in the model. These initial spacings were 25.0 x 25.0 ft. and 30.0 x 30.0 ft. based on work by Reid and others (2007). It was assumed that the plantation was being managed for either timber or nuts, not both at the same time.

RESULTS

Table 2 shows willingness-to-pay for deer damage abatement on timber plantations with initial spacings from 10.0 x 10.0 ft to 14.0 x 14.0 ft and various discount rates ranging from 3 to 8 percent. Based on the assumptions of the model, the range of values that would reflect a landowner's willingness to pay for deer abatement in a young timber stand would range from $13.18 to about $91.47 per acre. What this indicates is that if landowners are managing this timber as an investment and have planted the trees on 10.0 x 10.0 ft spacing, then they can invest $91.47 per acre on deer protection and still earn a 3-percent return on the

Table 2—Willingness-to-pay for deer abatement for different initial planting densities and discount rate

	Discount Rates					
Initial spacing	3%	4%	5%	6%	7%	8%
10'x10'	$ 91.47	$ 56.10	$ 38.90	$ 30.30	$ 25.86	$ 23.43
12'x12'	$ 76.54	$ 44.76	$ 24.92	$ 22.08	$ 18.35	$ 16.39
14'x14'	$ 80.91	$ 45.65	$ 28.45	$ 19.89	$ 15.50	$ 13.18

Table 3.—Willingness-to-pay per acre for deer abatement in nut production given two common initial planting densities and discount rates

	Discount Rates					
Initial spacing	3%	4%	5%	6%	7%	8%
25'x25'	$ 203.87	$197.44	$191.61	$186.29	$181.39	$176.85
30'x30'	$ 141.58	$137.12	$133.07	$129.37	$125.97	$122.81

timber investment. However, if the landowners are interested in earning 8 percent on that same plantation, then only $23.43 per acre can be spent for deer protection. This low willingness-to-pay reflects the fact that the benefit received for investing in deer protection on black walnut managed solely for timber is not justified by the cost of the deer protection. This way of thinking may be the reason that very few of the landowners throughout Missouri who are growing black walnut for timber actually spend the time and effort to protect those young seedlings.

On the other hand, landowners who are growing eastern black walnut for nut production present a different situation. Table 3 shows the willingness-to-pay for deer damage abatement for nut production at two different spacing recommendations and various discount rates. Values for willingness-to-pay range from $122.81 to $203.87 per acre. What this means is that if a landowner wishes to make a return of 8 percent from nut production and the initial spacing was 30.0 x 30.0 ft, it may be difficult to justify investing in deer protection for those young trees. Or, put another way, a landowner with initial spacing of 30 ft x 30 ft can invest $203 per acre for deer protection and still earn a 3-percent rate of return on the investment. As was expected, the willingness-to-pay for deer damage abatement in a plantation being maintained for nut production is considerably higher than the willingness to pay for deer abatement in plantations managed for timber.

DISCUSSION

It should be emphasized that this study was a preliminary look at the cost of deer damage and its economic impact on the production of black walnut timber and nuts. Many risks are associated with the production of timber or any other long-term investment. Deer damage is just one such risk. While inspecting the trees for deer damage, we saw evidence of degradation not caused by deer, such as frost cracking and insect damage. In addition to these factors that affect quality, two other factors were noted that probably have the most impact: proper site selection and good genetics.

Another factor that was not considered in this discussion is the impact of good weed control on the growth of the tree and the risk of deer damage. Obviously, with good weed control a tree will grow faster, but the relationship between faster growth and the risk of deer damage is not known. For this analysis, growth rate was assumed to be a constant.

Also, the impact of deer protection on the risk of deer damage was not considered in this study. Only two samples were taken in areas with deer protection. The deer protection used consisted of wire caging. It appeared that the deer protection had no impact on the amount of damage to the trees. In fact, both stands that had the wire caging had 16 percent of the trees either critically or severely damaged and the other stand had (compared to 22 and 28 percent on Site A and 14.57 percent on Site B, both without deer protection). In many cases, the deer actually bent the wire cages to get to the tree, or pushed the wire cages over in order to reach the tree.

As was expected, the willingness to pay for deer abatement in timber production was very low. In reality, a landowner interested in planting black walnut for future timber production will start with hundreds of seedlings per acre and eventually thin to less than a hundred per acre. If deer or other wildlife destroy a third of the young seedlings, the only real loss is the cost of the seedling and labor. Some may argue that potential veneer trees may be degraded by deer damage; however, over the long-term course of the plantation those risks are minimal.

On the other hand, landowners who plant black walnut for nut production face an entirely different set of options. Nut production requires more orchard management and returns income sooner than timber production. As a result, establishment and maintenance costs are higher. The impact on income of losing both the more expensive seedlings and the years of production is greater. In many cases, landowners who are interested in nut production will have as much as $15 per seedling invested and are expecting to generate some income from that investment as early as 10 years after planting. If deer or other wildlife destroys that seedling then the landowner is out not only the cost of the seedling but also the potential revenue starting at the tenth year and running into perpetuity. As expected, a landowner can afford to spend more for deer abatement in these types of plantations.

The objective of this paper is to determine how much a landowner should pay for deer damage abatement. Numerous methods claim to be effective at preventing deer damage, and costs range from $40 per acre for bar soap methods to $600 per acre for fencing (Pierce and Wiggers 1997). Although the effectiveness of many of the noncommercial methods is questionable, these methods are the very ones landowners are likeliest to use. The values calculated from this preliminary study explain why. For black walnut protection, many of the more effective methods of deer abatement are too expensive.

Future research on the cost of deer damage should focus on the impact of deer damage on timber trees from the perspective of sawmill product yield and recovery. Young trees damaged by deer may survive; however, the wounds caused by buck rub and browsing that penetrates the cambium may show up at the mill as the log is being processed. The expectation that a log removed from a plantation may have some unseen internal damage, could create a negative bias toward the value of the plantation as reflected in future prices offered for stumpage or logs.

Some of the challenges faced during this study included distinguishing between deer damage and other forms of damage. It became evident that deer are only a small risk factor when it comes to production of high- value timber. Another challenge was trying to incorporate growth factors, cost factors, and management factors over a long time period in order to get a model that would reflect reality. The Black Walnut Financial Model has many caveats; however, this type of financial analysis could not have been done without the timber growth financial analysis provided by that model.

In conclusion, this study was designed to look at the cost of deer abatement from the perspective of how much could be spent to prevent damage as opposed to looking at the discounted value of how much was actually spent. The difference between the two perspectives is determined by calculating the willingness-to-pay value. Landowners can then decide where their investment strategy falls within the range of values calculated. With a discounted cost method, the decision about the method of abatement is predetermined and the landowner is faced only with the results of selecting that method. Calculating willingness-to-pay provides more flexibility in the decision process.

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WEST VIRGINIA FOREST INDUSTRY TRANSPORTATION NETWORK ANALYSIS USING GIS

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Abstract.—To better understand and increase efficiency in delivery of harvested roundwood on West Virginia's roadways, a detailed network analysis using Geographic Information Systems (GIS) was conducted. Typical proximity-based analysis, which looks at straight-line distances (buffers) around given features regardless of terrain and road characteristics, provides limited knowledge of true transportation costs, i.e., travel time. This is especially evident in West Virginia's roadways, of which there are far fewer flat and straight than a proximity analysis would suggest. Furthermore, 6,343 bridges currently are associated with these roadways, many with weight restrictions that limit the effectiveness of proximity-based analysis.

To better serve the forest industry, a Timber Supply Area was established to understand how West Virginia road transportation systems correspond to the available hardwood resource. A transportation network analysis using U.S. Census road networks with associated speed limits, and current primary producing mill locations, were used to identify Sawmill Service Areas based on drive times. Sawmill service areas coupled with available private forest lands, using both grid- and vector-based analysis, provide a more comprehensive analysis of transportation costs.

INTRODUCTION

The West Virginia timber supply and sawmills that require raw logs for processing are connected by the log trucks that traverse the complex network of roads. In the Appalachian region, loggers identified trucking as one of the more limiting segments of the forest harvesting process, especially for small producers (Luppold and others 1998). A limited supply of trucks, longer haul distances, and increasing fuel costs (Mendell and others 2006) all contribute to the need for a better understanding and planning of the timber transportation networks that connect the forest resources and processing facilities.

Trucking distances play a very important role in the overall costs, productivity, and availability of trucking resources. Usually, the longer the distance a truck must travel, the higher the variable costs in labor, fuel, and required maintenance and the lower the overall productivity in volume of timber moved. By spatially identifying discrete commercial forest lands and the locations of sawmill processing facilities, we can analyze transportation networks to identify potential timber resources available within a transportation-economical range of each mill.

OBJECTIVES

The connections between timber supplies and sawmills can be investigated through network and suitability analyses using Geographic Information Systems (GIS). These analyses incorporate the more than 250,000 private forest landowners who control more than 90 percent of the State's forest land (Magill and others

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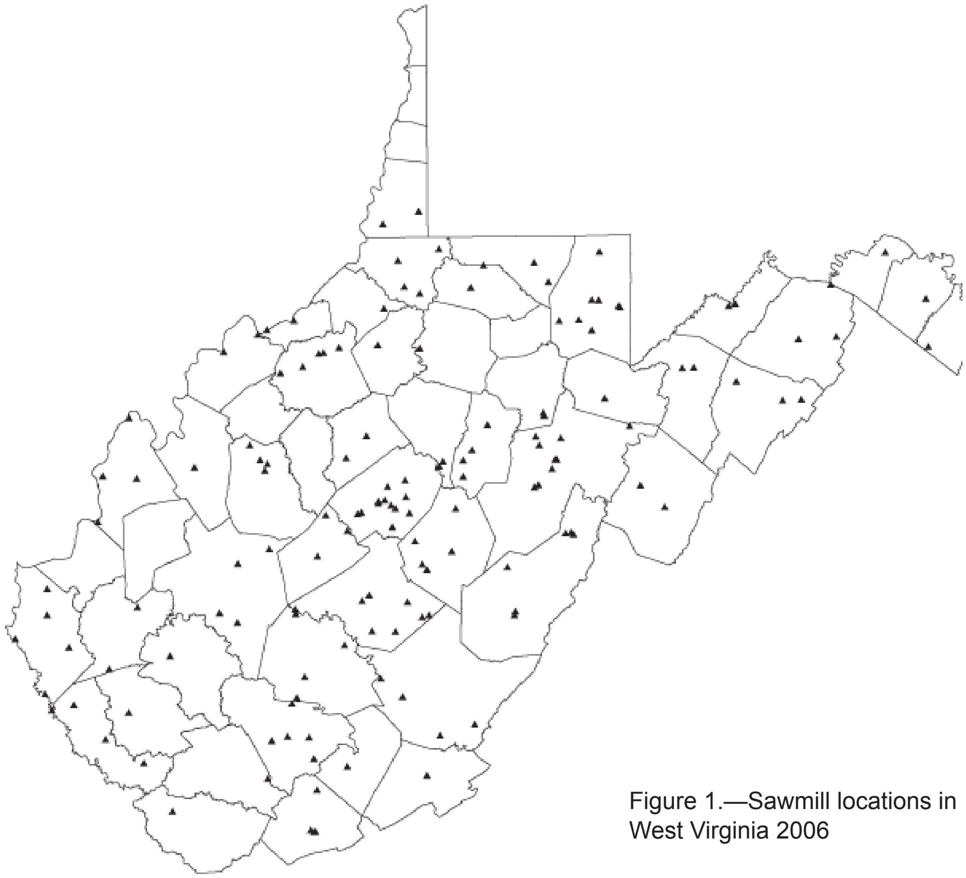

Figure 1.—Sawmill locations in West Virginia 2006

2004), and land-use suitability criteria that establish the appropriateness of the land for timber production. These Timber Supply Areas (TSAs), or areas throughout the State that are appropriate for commercial timber production are identified by distinguishing high quality private forest lands from all other land types. Sawmill Service Areas (SSA), or those areas (on any land use) that are within an economically feasible distance from West Virginia's 156 sawmills (Fig. 1), can also be identified. This analysis uses several statewide data layers associated with the hardwood forest resource and industry, including: topographic slope, threatened and endangered species habitat, U.S. Census road networks, proximity to roads, low weight bridges, private forested land, U.S. Forest Service Forest Inventory and Analysis (FIA) county data, existing forest stewardship lands, and sawmill locations. Each of these layers is combined using GIS to evaluate the transportation time of harvested timber from each identified TSA to existing sawmills.

This analysis process can provide a better understanding of the true area accessible to a sawmill based on log-truck travel times. The process also identifies timberlands that are not well served by primary processors. In fact, the TSA areas outside the reach of existing sawmills may be quality locations where new wood-product processing facilities could be located.

METHODS

To understand the transportation time involved in this study, TSAs were first established by means of a multi-layer overlay. Network analysis was then used to create SSA polygons. Finally, the SSA was overlaid on the TSA to calculate percentage overlap with each SSA. The data layers and processes used in the analysis are detailed in the following sections.

Analysis Mask

Model Builder in ArcGIS 9.2 (Environmental Systems Research Institute, Redlands, CA, 2006) was used to create an analysis mask (Fig. 2) that excludes areas outside the state boundaries and areas not considered private timberland (open water, urban areas, and National Forests, and other public lands) from the analysis.

Private Forested Lands

National Land Cover Data 2001 (Vogelmann and others 2001), developed from 30-m Landsat Thematic Mapper data from the Multi-Resolution Land Characterization Consortium, was queried for West Virginia land cover types representing forested land (Deciduous-41, Evergreen-42, and Mixed-43), and wetlands (Woody-91, Emergent Herbaceous-92).

Forest Patches

Roads, highways, and utility rights-of-way were subtracted from the private forest lands data from above in order to create a layer of forest patches. These patches were combined into operationally appropriate forest management patches of 1,000 acres (404.7 ha).

Threatened and Endangered Species

This data layer shows areas in proximity to threatened or endangered species habitat or blocks of land considered a unique or important habitat type. These blocks were derived from the West Virginia Division of Natural Resources (WVDNR) Natural Heritage Program database. All threatened and endangered species habitats from the WVDNR Natural Heritage database were selected and given a half-mile buffer, the recommended buffer distance developed by the WV Stewardship Planning Committee for the statewide stewardship program. These habitats were then converted to a 30-m grid and classified as areas not proximal to threatened or endangered species or areas in proximity using Boolean logic.

Topographic Slope

This raster data layer describes areas of West Virginia where slope is more than 5 percent and less than 40 percent. Percentage slope was derived from 30-m Digital Elevation Model raster files (U.S. Geological Survey 2006) using the ArcInfo Spatial Analyst Slope tool. The resulting grid cells were reclassified—1 for values between 5-40 percent and 0 for all remaining values.

Proximity to Roads

A road network dataset for West Virginia was extracted from ESRI's TIGER 2000-based StreetMap USA Nationwide Streets network dataset and a raster layer of all roadways was created with a 500-m buffer. This buffer approximates the maximum log skidding distances from the stump to a roadside landing. Those areas within the typical operational range for current logging systems were coded as close proximity, and those areas that exceed the 500-m distance were classified as not close proximity using Boolean logic.

Existing Stewardship Lands

Data layers from the WV Stewardship Spatial Analysis Project sponsored by the U.S. Department of Agriculture, identified approximately 630,000 acres of West Virginia forest land that is under forest stewardship. These areas are considered priority timber supply areas that are actively managed. Existing Stewardship Plan polygons were converted to a 30-m grid and classified according to whether a stewardship plan was present using Boolean logic.

FIA Data

Four datasets from the FIA program were used in this analysis. These data were as follows: volume of private growing stock on timberland by county; the volume of private sawtimber on timberland; the ratio of private growing stock removals to growth on timberland; and the ratio of private growing stock removals to growth on timberland. Mean values in each of these categories were calculated and used to classify each county as equal to or above the mean, or below the mean, using Boolean logic. This process was used to create four data layers that identify those counties with mean or above-mean volumes of growing stock on private lands, where growth of sawtimber exceeds the volume currently removed in harvesting.

THE OVERLAY MODEL

Model Builder

ArcGIS Model Builder was used for the TSA overlay model suitability analysis. This model spatially combines, by addition, the 11 data layers previously discussed. The analysis mask, which has a multiplier value of one, will force the analysis to occur only in areas with private timberland potential. Use of the mask will also ensure that all data layers overlay appropriately. Once the overlay model was implemented, the resulting TSA potential layer cell values were reclassified using the Natural Breaks classification algorithm to determine areas of low, medium, and high timber availability potential.

Sawmill Service Area Creation—Network Analyst

The road network dataset previously used had an additional data field that calculated travel time based on speed limit and road segment length. To enhance the routing accuracy of the service area polygons, a geometric data file with low-weight bridge locations (Gula 2007) identified the 584 bridge locations

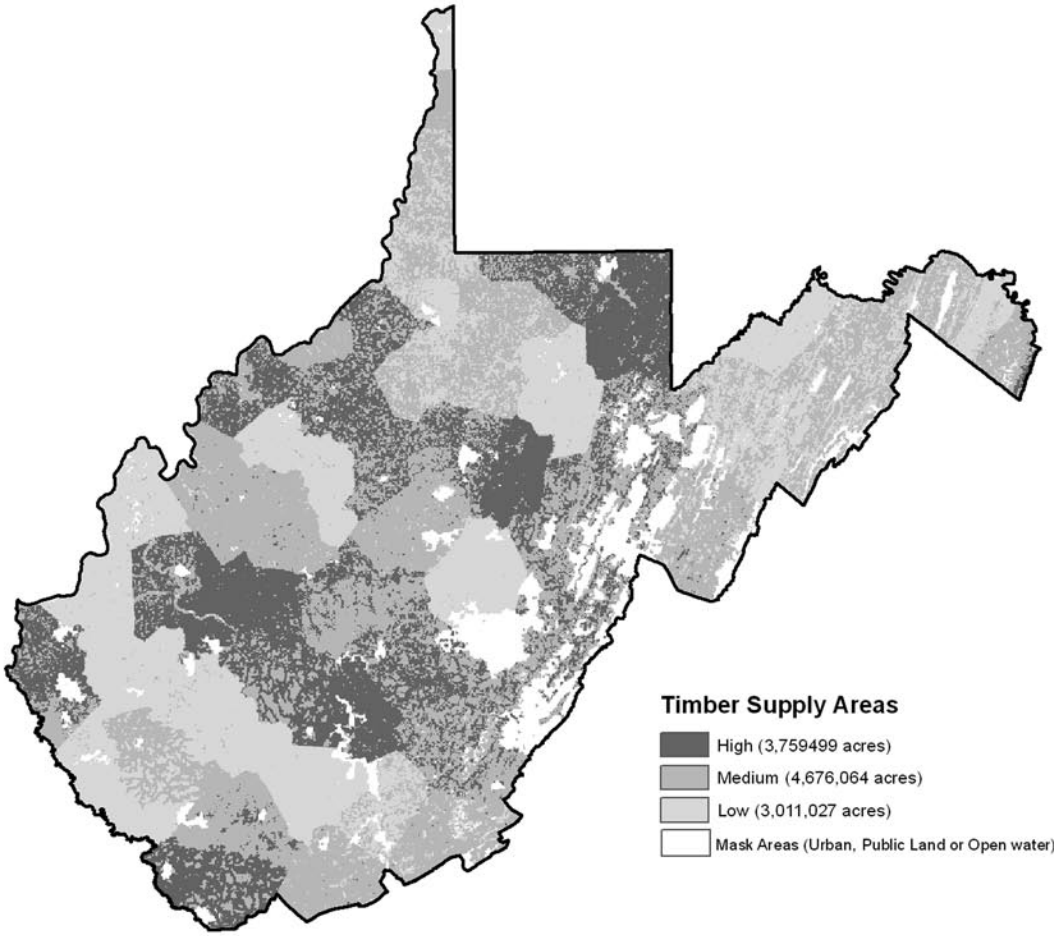

Figure 3.—Analysis layers used for the Timber Supply Areas (TSA) Boolean overlay suitability analysis.

throughout the State that have posted weight limits that do not meet requirements for typical log-truck weight classes (Spong 2007). Both bridges and sawmill location files were located on the network using a 2000-m search tolerance due to the difference in locations of the road network and feature locations. Fifteen sawmills were removed from the analysis because of ambiguous addresses.

Service area polygons were created using the ArcInfo Network Analyst extension. The service area tool was used to find actual roadway drive times in minutes based on driving towards each sawmill. To derive SSAs a 30-minute drive time was selected as an economically efficient drive time to the mill based on Barrett (2001). Resulting polygons were then loaded into the TSA overlay analysis to calculate the area in TSAs for each SSA.

RESULTS

Results from the overlay model determined that the majority of timberland area fell in the "medium" TSA category, followed by the "high" and then "low" categories (Fig. 3). The average area of the 156 SSAs was 211,907 acres with a minimum area of 60,246 acres and a maximum of 438,451 acres. On average, sawmills had 12.0 percent of their SSA in the "medium" TSA category (Table 1). This was followed by 8.6 and 8.3 percent of their area in the "high" and "medium" TSA areas, respectively. Median areas in the TSA categories were quite different. The median percent of SSA area in TSA was 1.5, 4.4, and 1.4 for the "high", "medium", and "low" categories, respectively (Table 1). Note that these values are averages of each of the 156 SSA components in the TSA categories and that the sum of these will not equal 100 percent.

Table 1.—Percentage summary and statistics of sawmill service areas classified as Timber Supply Areas (TSA) acres

156 Sawmills	Percent TSA high	Percent TSA med.	Percent TSA low
Average	8.62	12.00	8.31
Minimum	0	0	0
Maximum	65.71	69.94	68.60
Median	1.51	4.43	1.38
Std. Deviation	14.6	16.32	13.31

Approximately 1.2 million acres fell outside the 30-minute SSA for all mills analyzed in West Virginia. Most of the TSAs that did not correspond with an SSA were in the "low" category, followed by the "medium" and "high" categories (Fig. 4).

DISCUSSION

TSAs were ranked based on 11 data layers, each with some basic assumptions that would allow the model to identify areas that have more potential for greater volumes, quality, value, and accessibility. This ranking process provides the ability to identify potential TSAs using a wide variety of variables that are often too difficult to evaluate without advanced GIS analysis techniques. The data used to assess the relative quality of the TSA have been derived from many sources, which could pose to some problems. An obvious issue arises when addressing those areas that fall next to the state boundary. In these areas, road distances that are across state boundaries are not considered, potentially artificially suppressing the rank for a particular unit. Another issue comes from the scale at which the data have been collected. In data layers such as that for threatened and endangered species, the location points have been identified precisely, while FIA data have been summarized and presented at a county scale. To address this inconsistency, additional analyses that utilize more robust classification schemes, rather than the simple binary classes used in this analysis, can be used. Alternatively, a sensitivity analysis could clarify the importance (or unimportance) of the differences in data resolution.

The SSAs developed here provide additional information, as they help define haul-distance limits based on travel times. A sawmill that can procure logs from closer locations would be at an advantage over mills that are required to haul a much longer distance. As time can roughly be used as a proxy for cost (Martin 1971), the farther the haul distance to the mill, the more expensive the haul. While independent trucking contractors are often responsible for the direct cost of trucking, sawmills will incur the increased costs of long-distance hauls as the trucking costs (and all other costs to get the log to the sawmill) are applied to the value of that log. Barrett (2001) reported that one-way travel times longer than 30 minutes have a much greater percentage of the total trucking cycle time comprised of road travel. With the SSA set at a 30-minute one-way travel time, operations are more likely to be limited by loading, unloading, and delay times rather than the on the road travel time. Given that all haul distances will require loading, unloading, and some sorts of delay, those travel times more than 30 minutes have a greater impact on overall travel distances. Again travel routes are limited by both weight-restricted bridges and roads that travel outside of the state boundary. This limitation is best illustrated by the significant number of TSAs outside of SSAs in the northern panhandle area of the state (Fig. 4). In this area, sawmills located in adjacent states may have an SSA that does incorporate these West Virginia TSAs.

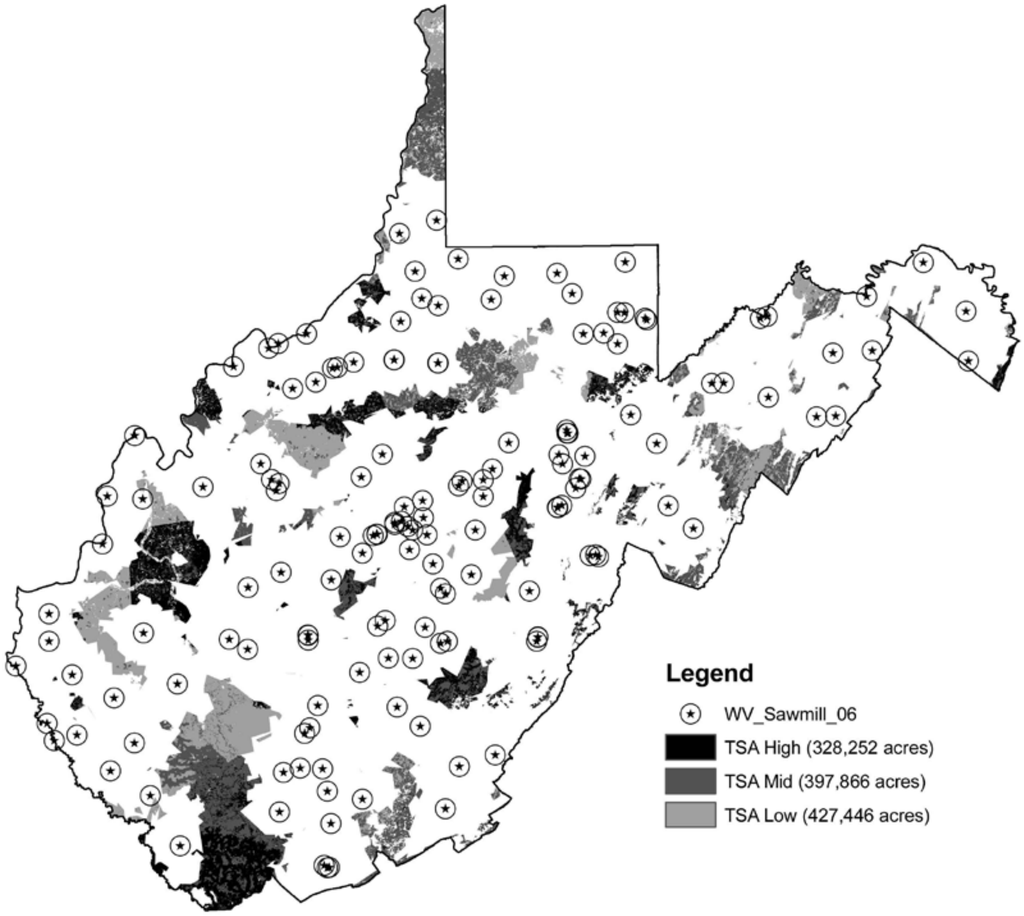

Figure 4.—Timber Supply Area (TSA) that are outside of 30-minute haul time to mills.

CONCLUSION

This analysis combines many different spatial components of the timber supply and processing activities. There are some obvious concentrations of sawmills located in the state, while there are many other areas that appear to be under-represented by sawmills. Specifically, those areas that are outside of the existing SSAs and have high TSA rankings are areas where new sawmills could be established and have relative advantages over competitors with longer haul distances and/or lower TSA rankings. While this analysis concentrated on sawmills and timber supply, the models and methods used here can provide both graphical and numerical summaries of a multitude of complex criteria to industry decisionmakers.

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EXPLORING THE OPTIMAL ECONOMIC TIMING FOR CROP TREE RELEASE TREATMENTS IN HARDWOODS: RESULTS FROM SIMULATION

Chris B. LeDoux and Gary W. Miller[1]

Abstract.—In this study we used data from 16 Appalachian hardwood stands, a growth and yield computer simulation model, and stump-to-mill logging cost-estimating software to evaluate the optimal economic timing of crop tree release (CTR) treatments. The simulated CTR treatments consisted of one-time logging operations at stand age 11, 23, 31, or 36 years, with the residual stands projected to their optimal economic rotation. The logging costs and revenues were estimated for the initial entry and for harvest at the optimal economic rotation. For comparison, the cost of CTR using hack-and-squirt herbicide treatments were computed as an alternative to the logging treatments at each age. The rotation age and final harvest were assumed to be the same for the logging and herbicide alternatives. The cumulative present net worth was used to compare the alternatives. When the rotation age was held constant at 100 years, the optimal economic timing for CTR using ground-based logging systems began at about age 27 and continued until about age 36. For the herbicide method, the optimal economic timing for CTR started at about age 20 and continued to about age 34. The results are useful to forest managers, landowners, and policy makers when considering CTR treatments in young hardwood stands.

INTRODUCTION

Crop tree release (CTR) is a widely applicable silvicultural technique used to enhance the performance of individual trees. It offers flexibility in that it can be applied on small or large properties, and with certain modifications, it can be applied as a precommercial or commercial operation. By favoring the development of selected crop trees within a hardwood stand, the landowner can meet a variety of area-wide management objectives, such as wildlife habitat, recreation, timber value, esthetic beauty, and species diversity. CTR can be applied at various stages of development, including sapling, pole, and sawtimber stands, depending on the specific opportunities to improve stand conditions (Perkey and others 1994, Perkey and Wilkins 2001).

CTR is applied by increasing the growing space around the crowns of desirable trees (Lamson and others 1990). The treatment entails eliminating trees that are limiting the horizontal crown expansion of the crop tree, thus increasing its free growing space. A "crown-touching" release is applied to deaden, fell, or harvest adjacent competing trees whose crowns touch that of the crop tree. The increase in growing space provides more sunlight and belowground resources to the crop tree. The crop tree then develops more leaf area in its crown, thus increasing photosynthesis and growth.

Traditional thinning techniques are intended to reach a desired area-wide residual stand density or remove specific sizes or crown classes of trees. CTR differs from traditional thinning in that it assures that most site resources are focused on a small number of selected trees rather than being widely distributed to all residual trees. CTR can be applied in both even-aged and uneven-aged stands; it is applicable in any situation where the forest manager intends to reallocate site resources to selected crop trees. While the term "crop tree" suggests a tree that has been selected for future harvest, in reality CTR can be applied to trees that will be

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either harvested in the future or retained for any number of years, depending on how they provide desired benefits or meet management objectives.

In young hardwood stands, the availability of crop trees is greatest when the canopy begins to close and continues for about 10-15 years after canopy closure. Young stands at canopy closure often contain in excess of 70 crop trees per acre, more than enough desirable trees to meet long-term management objectives. The stand age at canopy closure varies with site quality. On high-quality sites, where abundant resources accelerate stand development, canopy closure can occur at about age 8 to 10 years. On poorer sites, where fewer species are competitive and stand development is somewhat slower, canopy closure can occur at about age 13 to 15 years.

It is important to recognize that the number of potential crop trees declines with stand age. Each year a few potential crop trees succumb to the natural thinning process. In the absence of CTR treatments, stands older than 25 years often contain less than 30 to 40 crop trees per acre. In slightly older hardwood stands that are approaching large pole or small sawtimber size, there are still opportunities to release crop trees to improve vigor, growth, and spacing. However, beyond age 25 or 30 years the number of crop trees will continue to decline without CTR.

The timing of CTR treatments presents an important economic tradeoff between treatment cost and long-term benefit. Young stands contain the maximum number of desirable trees and the maximum opportunity to favor crop trees capable of increasing long-term stand value. However, young stands offer little merchantable wood volume to reduce treatment cost and they result in relatively longer investment periods (years until rotation age). Conversely, older stands contain bigger trees with more merchantable volume and relatively shorter investment periods. The problem with delaying CTR until operations are commercial is that the number of remaining crop trees can be greatly diminished in older stands, thus reducing the potential benefits of CTR. The tradeoff between cost and benefit in young stands leads to a critical management question: What is the optimal economic timing for CTR treatments?

OBJECTIVES

This report describes a method for exploring the optimal economic timing of CTR treatments in young Appalachian hardwood stands using stump-to-mill logging cost software integrated with a stand growth simulation model and discounted cash flow analysis. The results of this limited analysis indicate favorable stand ages for applying CTR and shed light on factors that affect the optimal timing of treatments.

METHODS

Stand Data

Data were obtained from 16 even-aged Appalachian hardwood stands, ranging in age from 11 to 36 years, on the Monongahela National Forest (MNF) in central West Virginia (Miller and others 2001). The stands were all located on the same ecological land type, defined by MNF personnel as the red oak series, and contained a mixture of upland hardwood species characteristic of northern red oak site index 70 on moderate 30- to 40-percent slopes.

Data from the 16 stands were stratified by age and stand structure was summarized at ages 11, 23, 31, or 36 years (Stands A, B, C, D). The summarized data included four stands at each age. For each age group, tree lists were developed to display total number of trees per acre (≥1.0 inches diameter at breast height [d.b.h.]), number of overstory trees per acre (only dominant and codominant crown classes), number of crop trees per acre (those trees that met species, vigor, and quality criteria), and number of harvest trees per acre (trees to be eliminated for the CTR treatment).

Species composition has a strong impact on economic returns in harvest operations, and even slight variability in species composition among the four groups of stands was a potential source of bias in exploring the optimal timing of CTR treatments. The distribution of the 81 crop trees found in the 11-year-old group was 30 percent yellow-poplar, 19 percent black cherry, 14 percent chestnut oak, 14 percent northern red oak, and 23 percent others. The number of crop trees averaged 56, 31, and 16/ac in the 23-, 31-, and 36-year-old stands, respectively. To provide for a valid comparison of economic returns among the four stand ages, the species composition (proportion of crop trees by species) for each age was adjusted to reflect the average species composition found in the 11-year-old stands. Similarly, the dominant and codominant trees competing with the crop trees in the 11-year-old stands were 3 percent yellow-poplar, 3 percent black cherry, 6 percent chestnut oak, 4 percent northern red oak, 15 percent red maple, 41 percent black birch, 4 percent pin cherry, 13 percent black locust, and 11 percent other commercial species. The species composition of competing trees also was adjusted to reflect that found in the 11-year-old stands.

LOGGING SYSTEM

The ground-based logging system assumed for the simulation was a John Deere 440 skidder (Deere and Co., Moline, IL) with chainsaw felling. The logging system remained the same for all simulations, including both CTR at various ages and the final harvest. The 70 horsepower JD 440C is considered a small skidder that is suited for skidding small-diameter logs such as those in the CTR treatment (LeDoux 2000, LeDoux 2007). The stump-to-mill logging costs were simulated for each treatment. It was assumed that no new road construction was needed, as the CTR treatments were simulated on sites that had been previously harvested. The one-way mileage to the sawmill or pulpwood plant was held constant at 25 miles. The logs were transported on traditional tandem trailer log trucks.

Model Used

MANAGE-PC (LeDoux 1986) integrates harvesting technology, silvicultural treatments, market prices, and economic returns over the life of a stand. The simulation combines discrete and stochastic subroutines. Individual subroutines model harvesting activities based on the silvicultural treatment, growth and yield projections, market prices, and discounted present net worth (PNW) economic analysis. MANAGE-PC was used to estimate volume yield, logging costs, logging revenues, and economic rotation length for each alternative.

The tree lists associated with CTR treatments at various stand ages were used as input to the simulation model and stand growth was projected in 5-year intervals until it reached its optimal economic rotation defined by the maximum PNW.

The delivered prices for sawlogs and pulpwood were obtained from forest products price bulletins (Ohio Agricultural Statistics Service 2007, Pennsylvania State University 2007, Tennessee Division of Forestry 2007, West Virginia University Division of Forestry 2007) and averaged by species (Table 1). Pulpwood and lower quality logs reflect prices paid for wood used to produce fiber products such as Oriented Strand Board. The cost for CTR treatments using herbicides was \$0.91/ft^2 of basal area obtained from results of recent field trials (Kochenderfer and others 2001).

Table 1.—Delivered prices for sawlogs and fuelwood/pulpwood by species

	Product			
Species	Large[a] high-quality sawlogs	Medium[b] size and quality sawlogs	Small[c] low-quality sawlogs	Fuelwood[d]/ Pulpwood
	-----------$/Mbf (Int. ¼-inch)-----------			$/cord
Red maple	251	192	131	40
Red oak	561	397	225	40
Yellow-poplar	571	397	225	40
Black cherry	571	397	225	40
Chestnut oak	450	279	138	40
Black birch	200	180	150	40
Pin cherry	150	100	80	40
Black locust	150	100	80	40
Other noncommercial	150	100	80	40

[a]Minimum small-end diameter ≥13 in, length ≥10 ft.
[b]Minimum small-end diameter ≥11 in, length ≥8 ft.
[c]Minimum small-end diameter ≥10 in, length ≥8 ft.
[d]89 ft^3/cord, minimum small-end diameter ≥4.0 in that will not make large, medium, or small sawlogs.

Table 2.—Summary of stand structure and effect of CTR treatment by stand age

Inventory	Stand age when CTR applied (yrs)			
	11	23	31	36
	----------- number of trees/ac --------------			
All trees ≥1.0 inch d.b.h.				
Initial	1566	1324	735	518
Cut	367	218	143	106
Residual	1199	1106	592	412
Dominant and codominant trees only				
Initial[a]	648	320	229	153
Cut	275	118	93	70
Residual[a]	373	202	136	83
Crop trees	81	56	31	16

[a]Includes crop trees.

RESULTS

The pretreatment inventory (all trees ≥1.0 d.b.h.) indicated an average d.b.h. of 2.0, 3.3, 5.3, and 6.8 inches and average volume of 1377, 2148, 2875, and 3305 ft^3/acre at age 11, 23, 31, and 36 years, respectively. Table 2 illustrates the effect of simulated CTR treatments on stand structure by stand age. The abundance of crop trees declined from 81 to 16 trees per acre, and the number of cut trees required to apply CTR declined with stand age.

Table 3 contains the simulated results for each stand age when the crop trees are released using the logging method detailed above and projected to their optimal economic rotation. Stand A reached its optimal economic rotation at age 71 with a cumulative PNW of $14.10/acre. Stand B reached its optimal economic

Table 3.—Simulated results for crop tree release with logging system by stand at the optimal economic rotation age

Logging System	Stand A	Stand B	Stand C	Stand D
Release age (yrs)	11	23	31	36
Average d.b.h. of cut trees (in)	2.21	4.52	6.79	9.16
Trees cut (trees/ac)	367	218	143	106
Volume cut (ft^3/ac)	353.03	576.44	874.85	1217.74
Mill value ($/ac)	158.67	259.07	393.19	548.60
Logging cost ($/ac)	182.80	299.15	455.06	410.77
PNW[ab] of CTR harvest($/ac)	-15.68	-16.26	-18.34	33.58
Optimal economic rotation (ORA)(yrs)	71	68	76	76
Average d.b.h. at ORA (in)	9.14	9.98	14.73	12.89
Trees cut/acre at ORA	418	285	124	152
Volume cut/acre at ORA (ft^3/ac)	4555.61	3887.89	3986.21	3737.02
Mill value at ORA ($/ac)	2037.44	2042.59	4141.84	3101.87
Logging cost at ORA ($/ac)	1555.19	1322.46	649.24	557.32
PNW of final harvest at ORA[b] ($/ac)	29.78	50.02	177.26	129.14
Cumulative PNW both harvests ($/ac)	14.10	33.76	158.92	162.72

[a]Real discount rate = 4 percent
[b]Discounted to age 0

Table 4.—Simulated results for the unreleased crop trees by stand at the optimal economic rotation age

Logging System	Stand A	Stand B	Stand C	Stand D
Release age (yrs)	0	0	0	0
Average d.b.h. (in)	0	0	0	0
Trees cut (trees/ac)	0	0	0	0
Volume cut (ft^3/ac)	0	0	0	0
Mill value ($/ac)	0	0	0	0
Logging cost ($/ac)	0	0	0	0
PNW[ab] of CTR harvest($/ac)	0	0	0	0
Optimal economic rotation (ORA)(yrs)	86	98	76	66
Average d.b.h. at ORA (in)	9.24	12.73	12.82	12.99
Trees cut/acre at ORA	484	224	197	173
Volume cut/acre at ORA (ft^3/ac)	5178.28	5168.79	4675.71	4227.22
Mill value at ORA ($/ac)	2355.58	3033.52	3080.32	2734.53
Logging cost at ORA ($/ac)	1771.19	773.33	699.94	635.48
PNW of final harvest at ORA[b] ($/ac)	20.04	48.40	120.81	157.70
Cumulative PNW both harvests ($/ac)	20.04	48.40	120.81	157.70

[a]Real discount rate = 4 percent
[b]Discounted to age 0

rotation at age 68 with a cumulative PNW of $33.76/acre. Stand C reached its optimal economic rotation at age 76 with a cumulative PNW of $158.92/acre. Stand D reached its optimal economic rotation at age 76 with a cumulative PNW of $162.72/acre. Table 4 contains results for each stand age grown to its optimal economic rotation without CTR. The untreated stands reached their optimal economic rotation at ages 86, 98, 76, and 66 with cumulative PNWs of $20.04/acre, $48.40/acre, $120.81/acre, and $157.70/acre, respectively. The cumulative PNW results are compared in Figure 1. From age 11 to 23 years, PNWs

Table 5.—Simulated results for crop tree release with logging system by stand at rotation age of 100 years

Logging System	Stand A	Stand B	Stand C	Stand D
Release age (yrs)	11	23	31	36
Average d.b.h. (in)	2.21	4.52	6.79	9.16
Trees cut (trees/ac)	367	218	143	106
Volume cut (ft^3/ac)	353.03	576.44	874.85	1217.74
Mill value ($/ac)	158.67	259.07	393.19	548.60
Logging cost ($/ac)	182.80	299.15	455.06	410.77
PNW[ab] of CTR harvest($/ac)	-15.68	-16.26	-18.34	33.58
Assumed rotation (yrs)	100	100	100	100
Average d.b.h. at 100 yrs (in)	11.12	13.04	17.40	15.72
Trees cut/acre at 100 years	326	199	91	123
Volume cut/acre at 100 years (ft^3/ac)	5629.57	4955.88	4340.25	4858.87
Mill value at 100 years ($/ac)	2798.09	3495.43	5701.92	5267.16
Logging cost at 100 years ($/ac)	1940.02	749.94	570.48	837.53
PNW of final harvest at 100 yrs[ab] ($/ac)	16.34	52.27	97.70	84.33
Cumulative PNW both harvests($/ac)	0.66	36.01	79.36	117.91

[a]Real discount rate = 4 percent
[b]Discounted to age 0

Table 6.—Simulated results for the unreleased crop trees by stand at rotation age 100 years

Logging System	Stand A	Stand B	Stand C	Stand D
Release age (yrs)	0	0	0	0
Average d.b.h. (in)	0	0	0	0
Trees cut (trees/ac)	0	0	0	0
Volume cut (ft^3/ac)	0	0	0	0
Mill value ($/ac)	0	0	0	0
Logging cost ($/ac)	0	0	0	0
PNW[ab] of CTR harvest($/ac)	0	0	0	0
Assumed rotation (yrs)	100	100	100	100
Average d.b.h. at 100 yrs (in)	10.11	13.15	15.10	17.27
Trees cut/acre at 100 years	391	214	160	120
Volume cut/acre at 100 years (ft^3/ac)	5432.11	5352.61	5546.40	5621.23
Mill value at 100 years ($/ac)	2592.60	3223.14	4530.51	5455.80
Logging cost at 100 years ($/ac)	1858.17	815.87	930.85	738.72
PNW of final harvest at 100 yrs[ab] ($/ac)	13.99	45.83	68.53	89.81
Cumulative PNW both harvests($/ac)	13.99	45.83	68.53	89.81

[a]Real discount rate = 4 percent
[b]Discounted to age 0

were slightly greater with no CTR. At age 31 and 36 years, CTR resulted in a greater PNW. Although the results in Figure 1 are discrete points by stand age and the curves are linear between points, the results suggest that CTR would be beneficial starting at about age 25 and continuing to about age 36.

Table 5 displays results of simulated CTR assuming a fixed rotation of 100 years instead of the optimal economic rotations. For comparison, the stands were projected to a 100-year rotation without CTR (Table 6). The cumulative PNWs for the released stands at age 100 were $0.66/acre, $36.01/acre, $79.36/

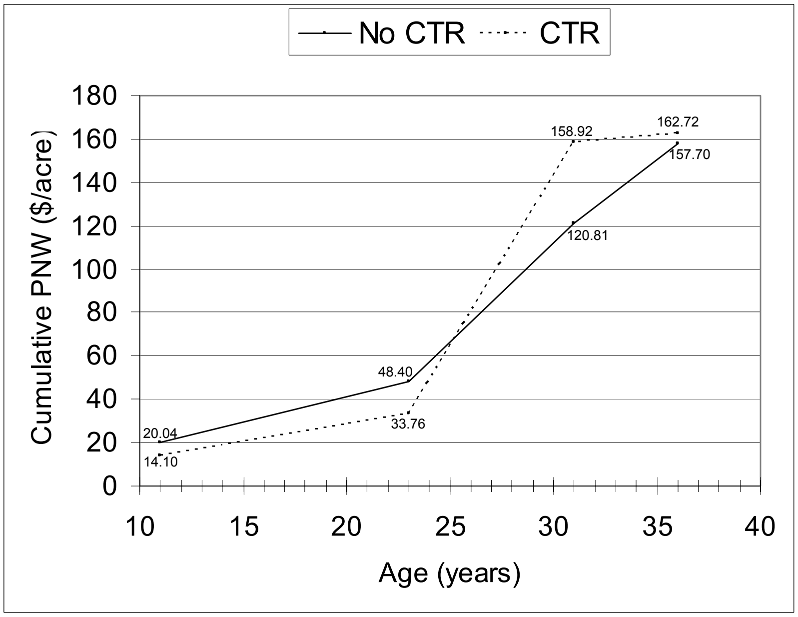

Figure 1.—Cumulative PNW by stand age at the optimal economic rotation age for crop tree released and unreleased stands using logging methods.

Figure 2.—Cumulative PNW by stand age for rotation age 100 of crop tree release and unreleased stands using logging methods.

acre, and $117.91/acre, respectively (Table 5). The cumulative PNWs for the unreleased stand were $13.99/acre, $45.83/acre, $68.53/acre, and $89.81/acre, respectively (Table 6). The cumulative PNWs for the released and unreleased stands are compared in Figure 2. Again, for ages 11 to 23 years, PNW was greater without CTR, and for ages 31 to 36 CTR provided a higher PNW.

Figure 3 illustrates the cumulative PNW curves for CTR using herbicides instead of harvesting, followed by growth to a 100-year rotation. The cumulative PNW differences for ages 11 and 23 were $1.52/acre and $0.25/acre, respectively. The cumulative PNW differences for ages 31 and 36 were $21.65/acre and $9.51/acre, respectively. The curves suggest that for ages 11 through 23, CTR with herbicides provides about the same benefits as not treating the stands. The economic benefit of treating very young stands is limited because the wood products harvested are small diameter and are not yet merchantable, and because the investment period to carry the treatment costs to final harvest is very long. We can also infer that for stands between ages 23 and 34 years, CTR with herbicides is better than no release treatment (Fig. 3).

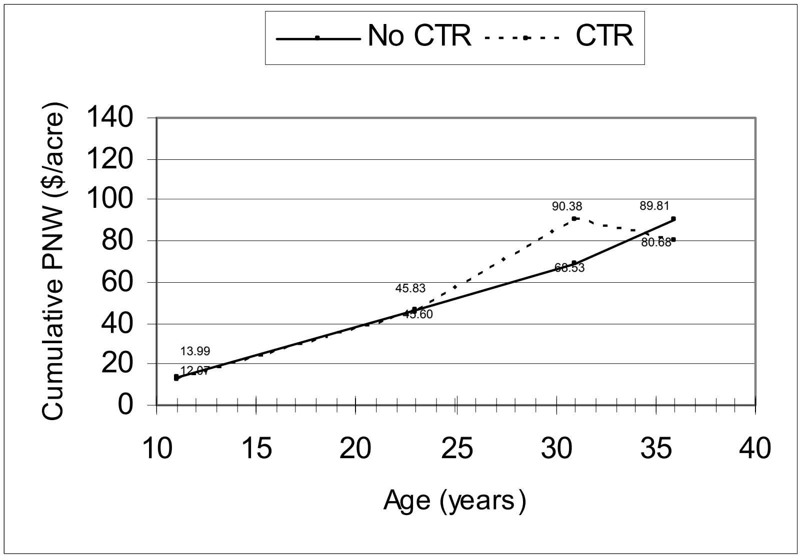

Figure 3.—Cumulative PNW by stand age for rotation age 100 of crop tree release and unreleased stands using hack-and-squirt injection methods.

As tree diameters increase with age, the wood products harvested begin to offset the treatment costs, and the investment period to carry the treatment costs to final harvest is shorter. The herbicide release is better than logging release between ages 25 and 30 (Fig. 4). This outcome is attributable to the fact that the herbicide treatment costs less than the logging method because the logging costs are not being offset by revenue from the harvested wood products. However, for stands age 35 and beyond the herbicide release has a lower PNW than the no-treatment alternative. In older stands, the long-term benefit of CTR is limited because the number of crop trees per acre is greatly reduced compared with younger stands. Moreover, the herbicide release does not yield merchantable products to offset the treatment cost. At stand age of 35 and beyond, it is better to release the stands with logging methods (Figs. 2 and 3). Using a logging method to treat the stand is better in the oldest age class tested here because the cut-trees provided an immediate net revenue (Tables 3 and 5) that offsets the logging costs and provides some profit for the landowner.

CONSIDERATIONS FOR MANAGERS

The results summarized in this paper are unique to the stand structure, site quality, species composition, stand ages, logging technology, herbicide treatment cost, the real discount rate of 4 percent, the simulation model used, and other assumptions made during the simulations. The results show what is possible when an integrated approach is used to evaluate the optimal economic timing of CTR treatments. There can be measurable economic advantages to applying CTR treatments when hardwood stands are young. As stands age, CTR can also be advantageous using logging methods since the trees removed can provide a positive cash flow at treatment time. For some stands, CTR may not provide an economic benefit and the stands should be allowed to grow untreated. Stands with extremely low or extremely high potential value are not good candidates for CTR. For example, stands with few crop trees offer little potential benefit for CTR because there is limited opportunity to affect long-term species composition and stand value. Similarly, stands with abundant crop trees of high value are likely to exhibit favorable long-term species composition without CTR. Finally, the opportunity costs of growing stands beyond the optimal economic rotation can be substantial (LeDoux 2004), although managers may wish to grow stands beyond the optimal economic rotation age for other objectives.

Figure 4.—Precommercial CTR using herbicides in this 21-yr-old mixed hardwood stand provides the highest PNW compared to the no-treatment or the commercial logging options. As stand age approaches 35 years, CTR using the commercial logging option provides the highest PNW.

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A METHOD FOR QUANTIFYING AND COMPARING THE COSTS AND BENEFITS OF ALTERNATIVE RIPARIAN ZONE BUFFER WIDTHS

Chris B. LeDoux and Ethel Wilkerson[1]

Abstract.—We developed a method that can be used to quantify the opportunity costs and ecological benefits of implementing alternative streamside management zones/buffer zone widths. The opportunity costs are computed based on the net value of the timber left behind in the buffer zone, the stump-to-mill logging costs for the logging technology that would have been used to harvest the timber, the prevailing pond values of logs delivered to the sawmills or processing plants, and the time value of money. By conducting a comprehensive review of the published scientific literature, we quantified the ecological benefits for select riparian functions based on their ability to protect against post-harvest changes. The riparian functions considered in this study were recruitment and supply of coarse woody debris, shade and temperature maintenance, sediment filtering, protection and maintenance of aquatic communities, and the protection and maintenance of habitat for riparian associated bird communities. The results can be compared using graphical displays and the principles of benefit/cost analysis. The method can be used by loggers, managers, and decision- and policy-makers to understand the costs and benefits of implementing alternative buffer zone widths to protect riparian functions.

INTRODUCTION

Riparian areas protect water quality and aquatic communities by reducing the amount of sediment entering the stream channel (Castelle and Johnson 2000), shading the stream channel from solar radiation (Brown and Krygier 1967), supplying organic material for food (Allan 1995), contributing woody material that increases the hydraulic and structural complexity of the stream channel (Hilderbrand and others 1997), and providing habitat for aquatic and terrestrial organisms (Bisson and others 1987). From an ecological perspective, riparian areas are among the most productive wildlife habitat on the continent (Kentucky Dept. of Fish and Wildlife Resour. 1990). Removal of riparian vegetation during forestry operations has been shown to increase the sediment load in the stream (Davies and Nelson 1994), increase water temperature (Brown and Krygier 1967), and change the food supply and/or habitat conditions(Hawkins and others 1982, Hanowski and others 2002), all of which alters the aquatic and riparian communities. Streams, wetlands, and riparian areas are among our most ecologically valuable natural areas. Leaving buffer strips adjacent to waterways can effectively reduce the water quality concerns associated with timber harvesting, agricultural production (e.g., Maisonneuve and Rioux 2001, Allan 2004, Schultz and others 2004, Schulte and others 2006), and lakeshore development (Kramer and others 2006).

The protection of riparian areas is a top priority for most state and federal conservation agencies (Blinn and others 2001). Protection of riparian areas is achieved by establishing streamside management zones (SMZs) adjacent to waterways and by adopting guidelines for locating haul roads, skid trails, log landings, and stream crossings (best management practices or BMPs). Recommendations for SMZs and BMPs vary

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among states (Huyler and LeDoux 1995, Shaffer and others 1998, Vasievich and Edgar 1998, Blinn and Kilgore 2001, Williams and others 2004). An Internet website (Timbersource.com/bmp/html) allows easy access to BMPs and SMZ management information on a state-by-state basis. For example, the recommended BMP for most SMZs include no harvesting activities in 15 to 45 m buffer strips adjacent to the waterway and/or allowances for up to 50-percent removal of the basal area/volume of standing trees leaving an evenly distributed/spaced stand to protect the stream and wetland (LeDoux and others 1990, Phillips and others 2000). Recommendations also vary among National Forests; for example, the Mark Twain uses riparian management zones (RMZs) and watershed protection zones (WPZs). The WPZ extends 30.48 meters (horizontal distance) on either side of the channel. Some activities are prohibited in the WPZ, such as log landings, road and skid trail construction, and the construction of wildlife ponds. Timber harvesting is allowed, but trees cannot be cut within 7.62 meters of the stream channel unless necessary to move the area towards the desired condition, or to facilitate designated crossings (Personal Communication, Charly Studyvin). By contrast, the Green Mountain and Finger Lakes National Forests use 7.62-m equipment-free zones on either side of the channel. Although logging equipment is prohibited in these strips, trees may be cut in them but must be winched out (Personal communication, Christopher Casey).

In addition to providing habitat for a wide range of game and nongame wildlife species, and providing a host of ecological services, riparian areas are some of the best sites for producing high-quality wood products. The unharvested timber left in SMZs can represent a substantial opportunity cost (Shaffer and Aust 1993, Kilgore and Blinn 2003, LeDoux 2006). The opportunity costs are influenced by the species mix in the stand, the logging technology used, the level of riparian protection desired (Peters and LeDoux 1984, LeDoux 2006), the stream network to be protected (Ice and others 2006), and the proportion of isolated SMZ units within a watershed (Olsen and others 1987, University of Washington 2003).

OBJECTIVES

Simultaneous economic and environmental assessments have been reported, addressing the consequences of alternative fuel management strategies (Mason and others 2003) and the layout and administration of fuel removal projects (Hauck and others 2005). Companion papers address the opportunity costs/capital recovery cost of managing for old growth forest conditions (LeDoux 2004), of alternative patch retention treatments (LeDoux and Whitman 2006), and of implementing streamside management guidelines in Eastern hardwoods (LeDoux 2006, Li and others 2006). In this paper, our objective was to document a method that can be used to quantify and compare the opportunity costs and ecological benefits of implementing alternative streamside management zones/buffer zone widths. This is the first attempt at modeling opportunity costs and ecological benefits for riparian areas in forested regions. Land managers are more likely to implement buffer zones if they understand the costs and benefits of doing so.

METHODS

Stand Data

The best data to use for this method are data on stands that are representative of the riparian area to be protected. Ideally, individual tree or cruise lists will be developed for the stands in question. The next step is to determine the economic rotation length that would apply to these riparian stands. A robust method for determining the optimal economic rotation is to use one of many growth and yield models to project growth of the stand to its optimal economic rotation. This approach yeilds the present net worth (PNW) for the optimal rotation, which is a necessary component for this method.

Logging System

The next step is to determine the type of logging technology that could be used to harvest the timber in these stands. The portion of the stands in the riparian zone to be protected will likely not be harvested, but the method requires the logging cost information to determine the net value of the timber in the SMZ. Once the logging technology is defined, then we can estimate the logging costs involved. Traditionally, time study data are used to compute logging costs. A more robust, user-friendly approach is to use stump-to-mill logging cost estimation software (LeDoux 1985).

Pond Values

The delivered prices for sawlogs and pulpwood can be obtained from forest product bulletins posted on the internet by individual companies or by universities. Alternatively, more accurate information on log prices can be obtained by contacting the wood-consuming industry located within a 30.48-m radius of the riparian area to be protected and requesting their price sheets. Most sawmills or timber procurers are more than willing to provide contemporary log and pulpwood price information upon request. The log and pulpwood price information along with the stand data is used to compute the gross dollar value of the timber to be left in the SMZ. The logging costs are then subtracted from the gross value to arrive at the net value of the timber left in the protection of the SMZ. The opportunity and capital recovery costs are then computed for each protection option. Pond values represent the cost side of the equation in this method, capturing the value lost by leaving timber standing in the riparian corridor.

Riparian Functions

The ecological functions and values of riparian zones are numerous and range from stabilizing near-stream soil (Castelle and Johnson 2000) to providing travel corridors for large terrestrial mammals (Klapproth and Johnson 2000). Riparian zones also have important social and culture value and can be important areas for recreation and community interaction (e.g., Cole and Marion 1988, Globster and Westphal 1998, Ryan and Walker 2004, Colby and Smith-Incer 2005). Quantifying the range of physical and biological functions and values that occur within riparian areas would be a daunting task. For this method, the focus should be on the processes and biota that are easily measurable and strictly dependent on and/or unique to riparian zones. In an application of this method (LeDoux and Wilkerson 2006), we limited the various functions of the modeled riparian forests to the following five categories: 1) coarse woody debris supply; 2) shade/temperature maintenance; 3) sediment filtering; 4) maintenance of aquatic communities (macroinvertebrates and periphyton); and 5) maintenance of riparian bird habitat (riparian associated passerines).

A literature review would be conducted to identify studies examining the riparian function of interest. Studies with SMZ widths similar to those in the planned project but that do not correspond exactly to the above ecological categories should be placed in the most logical category, while studies with large discrepancies in SMZ width or those using experimental design should be excluded from the review. Research results on the ecological assessment of SMZs may not exist in adequate quantities from a single region of the United States. To complete the analysis, one must focus on literature from the appropriate region of the country, but as data are limited it is desirable to include studies from other regions. The evaluation of SMZ protection options is limited to the published scientific results in the contemporary literature.

Table 1.—SMZ protection scores for different SMZ widths for protecting against post-harvest changes in riparian functions for 2nd to 4th order streams (from LeDoux and Wilkerson 2006)

Riparian Function	Width				References
	No SMZ	15 m	30 m	45 m	
Coarse woody debris	0[a]	1	2	3	Murphy and Koski 1989, Harmon and others 1986, McDade and others 1990, Robinson and Beschta 1990, Van Sickle 2000, May and Gresswell 2003.
Shade/ temperature maintenance	0	2	3	3	Burton and Likens 1973, Moring 1975, Brown and Krygier 1967, Rishel and others 1982, Lynch and others 1984, Lynch and others 1985, Noel and others 1986, Beschta and others 1987, Budd and others 1987, Caldwell and others 1991, Kochenderfer and Edwards 1991, Davies and Nelson 1994, Jackson and others 2001, Kiffney and others 2003, Wilkerson and others 2006
Sediment filtering	0	2	2	3	Karr and Schlosser 1977, Moring 1982, Lynch and others 1985, Davies and Nelson 1994, Jackson and others 2001
Aquatic communities (macroin-vertebrates and periphyton)	0	2	3	3	Newbold and others 1980, Noel and others 1986, Davies and Nelson 1994, Hetrick and others 1998, Kiffney and others 2003, Wilkerson and others, in reviewb
Riparian bird communities (riparian-associated passerines)	0	2	3	3	Triquet and others 1990, Whitaker and Montevecchi 1999, Pearson and Manuwal 2001
Total Score	0	9	13	15	
Percent SMZ effectiveness	0%	60%	87%	100%	

[a]Scoring: 0) Does not protect riparian function; 1) Results in moderate post-harvest changes in riparian function; 2) Results in small post-harvest changes in riparian function; 3) Completely protects against measurable changes in riparian function

Ranking/Scoring System

For each SMZ width the next step is to assess the capacity of the SMZ to protect against post-harvest changes for each of the categories of riparian function based on the following criterion:

- (score =0) the SMZ does not protect the component, resulting in large post-harvest changes
- (score =1) SMZ results in moderate post-harvest changes
- (score =2) SMZ results in small post-harvest changes
- (score =3) SMZ protects against major changes in the component

Scores are determined by comparing the magnitude of expected changes with and without the SMZ of that width. The statistical significance of post-harvest changes found in the studies reviewed gives a good indication of protection. Based upon this scoring method, each SMZ width is given a numerical score (0-3) for each of the five categories of riparian function. An overall score for each SMZ width is calculated by summing the score of each category of riparian function (Table 1). The overall scores have a minimum value of 0 and a maximum value of 15. To calculate the SMZ protection score, the overall score is then converted into a percentage with 0 percent representing no protection of riparian functions (value of 0) and

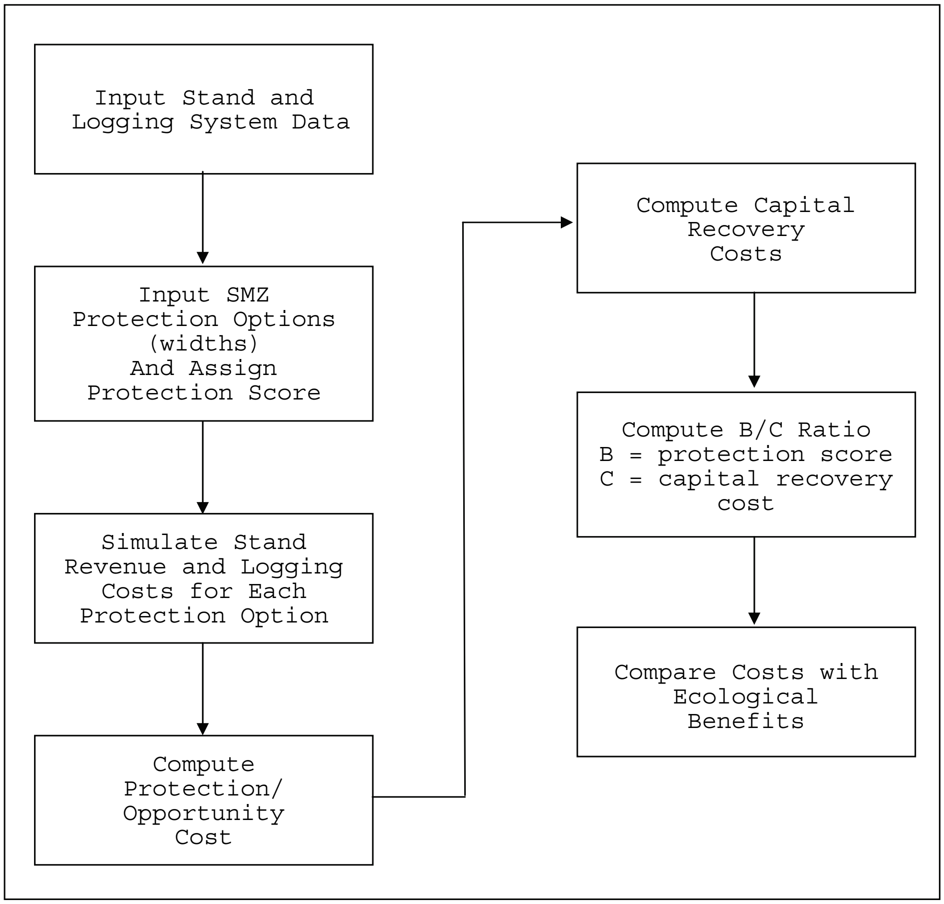

Figure 1.—Design flow diagram.

100 percent representing complete protection against measurable changes in riparian functions, creating conditions similar to undisturbed riparian areas (value of 15).

SMZ Protection Options

The stands are then modeled for computer analysis considering any assumptions necessary. SMZ protection options that could be evaluated include:
no protection

- unharvested 15-m SMZ on both sides of the stream
- unharvested 30-m SMZ on both sides of the stream
- unharvested 45-m SMZ on both sides of the stream
- a partial harvest of alternative SMZ widths on both sides of the stream with alternative percentages of the timber volume removed from the SMZ (Li and others 2006).

Although most RMZ guidelines call for removing some volume (Blinn and Kilgore 2004), users can evaluate the opportunity costs and ecological benefits for more restrictive treatments, such as not allowing any wood to be removed from within the SMZ.

Sample Application

The general procedure is shown in the flow diagram in Figure 1. In order to illustrate how this method works, we borrow data and results from LeDoux and Wilkerson 2006 and from LeDoux and Wilkerson

2007. In the example we considered two stands, four logging technologies, five riparian functions, and four SMZ protection options. In this example we use the published scientific data that are currently available. We interpolate estimates between known discrete data points for the five riparian functions and SMZ protection options. For example, Figure 2 assumes that the relationship between capital recovery cost and SMZ protection score is linear. We fit curves to the four data points from Table 3. We then compute the slopes between the data points for comparison. We realize that the available data are not complete or in the most desirable format for the type of integration we are conducting in this research. We make these assumptions and interpolate between known discrete data points in order to complete the research. As more refined data become available, they will be incorporated into the analysis. In some cases we simply do not have data available. Thus we interpolate or simulate values between known data points. Although this approach is not as robust as using observed values, it does help understand the opportunity cost and ecological tradeoffs involved in using alternative buffer zone widths. Table 1 shows the protection scores and percent SMZ effectiveness for five riparian functions and four SMZ protection options. Table 2 shows the logging system configurations used in the example.

For evaluation, decisionmaking, and policy analysis, the costs and benefits of implementing alternative buffer zone widths can be compared using graphic displays (Figs. 2 and 3), benefit/cost ratios (Table 3), or the change in SMZ protection scores versus capital recovery costs (Fig. 2) between simulated buffer widths. For example, Figure 3a and 3b show that gross and net revenue by stand and logging technology decrease as wider buffer zones are implemented. Gross and net revenues also decrease as more expensive logging technology is used (logging technology A versus logging technologies C and D). The curves in Figure 2 show that although the capital recovery costs increase in a linear fashion, the SMZ protection score levels off in a nonlinear fashion, suggesting that the protection score decreases as wider buffer zones are implemented. The benefit/cost ratios shown in Table 3 suggest that as wider buffer zones are used, the ratio of ecological benefit to the cost differential required to obtain that benefit decreases with stand tree species composition, logging technology, and SMZ protection score. Figure 2 also shows change with respect to SMZ protection score and capital recovery cost between simulated buffer zone width points. For example, the slope between buffer zone width of zero and 15 m is 5.89, suggesting that the ecological benefit is responding aggressively as buffer zone widths go from no buffer zone (width=0) to buffer zones that are 15 m wide. The slope between 15-m and 30-m widths is 2.65, implying that the ecological benefit of going from 15- to 30-m widths is decreasing compared to going from 0 to 15-m widths. The slope between 30- and 45-m widths is 1.28, much smaller than the previous two slopes. Going from 30- to 45-m widths appears to provide marginal benefits in comparison to 15- and 30-m widths.

CONSIDERATIONS FOR MANAGERS

There is no question that land managers and owners need to protect water quality and riparian area functions when considering forest operations adjacent to or within such areas by using buffer zones. However, it is clear that leaving trees of value within these buffer zones can represent a substantial financial loss in the short and long term to the landowners. A desirable outcome would be to strike a balance where riparian functions and areas are protected and monetary losses are minimized. The method documented in this paper could be used to arrive at these balance points or to understand the tradeoffs involved in implementing alternative buffer zone widths. Using these methods will not solve all the problems and challenges of selecting the correct buffer zone widths, but it can provide information that integrates the short- and long-term costs and ecological benefits of the alternatives, information that can help managers

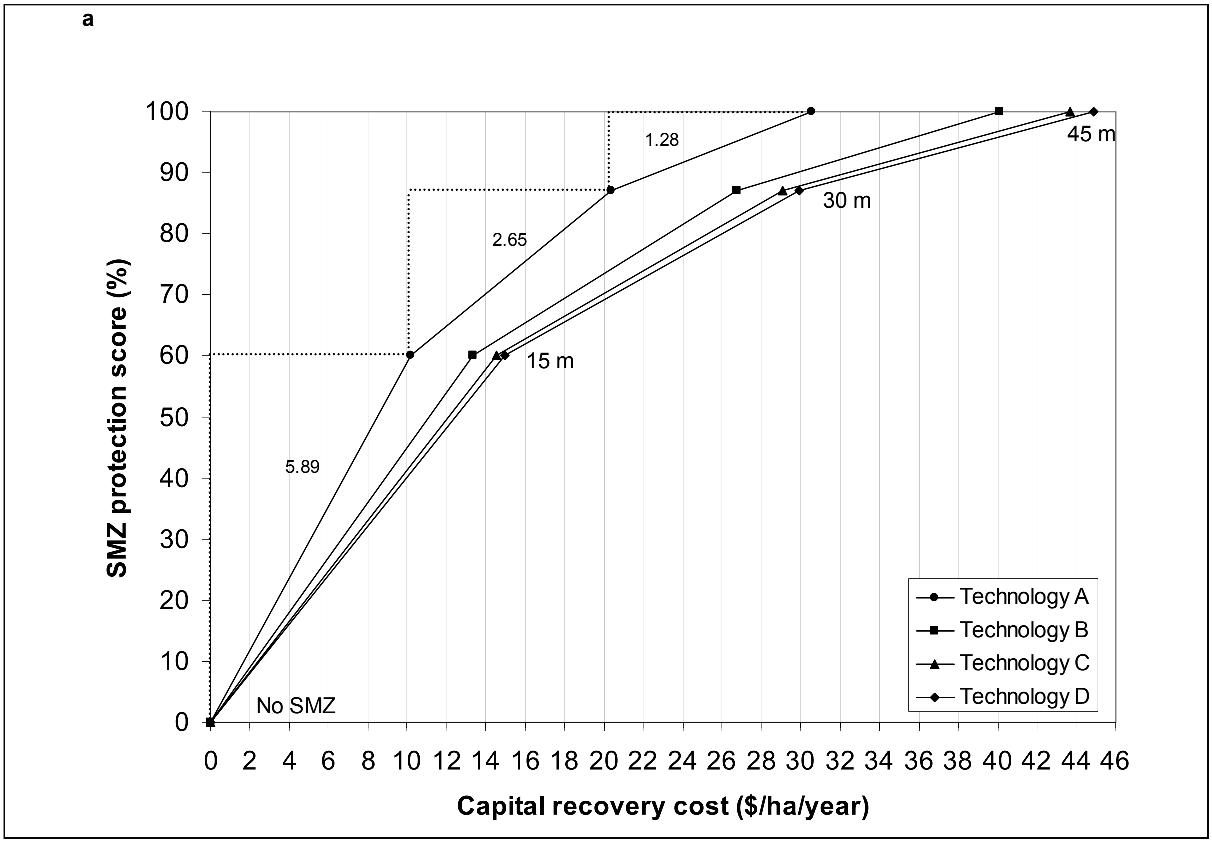

Figure 2.—SMZ protection scores compared with capital recovery costs for the (a) yellow-poplar stand under the four harvesting technologies. Symbols and lines represent different logging systems. SMZ protection scores are labeled on corresponding SMZ width (See Table 2 for description of technologies used) (from LeDoux and Wilkerson 2007).

Table 2.—Logging system configurations and costs used to simulate the harvest of the 27.5-ha tracts (from LeDoux and Wilkerson 2006)

		Cost/unit ($/m^3)	
Logging technology	Description	Yellow-poplar stand	Mixed hardwood stand
A	Chainsaw felling with Ecologger I cable yarder	20.83	20.47
B	Timbco 445 Cut-to-length harvester with Valmet forwarder	17.65	17.30
C	Chainsaw felling with John Deere 640 cable skidder	16.24	16.24
D	Timbco 425 feller buncher with Valmet forwarder	15.88	15.88

make better decisions. An additional topic to consider is landowners' acceptance of different land management practices on their land, and in riparian buffer zones specifically. Landowners' attitudes and views on management practices will influence what they are willing to implement on their land regardless of some of the economic implications (Schrader 1995, Kline and others 2000, Shindler and others 2002).

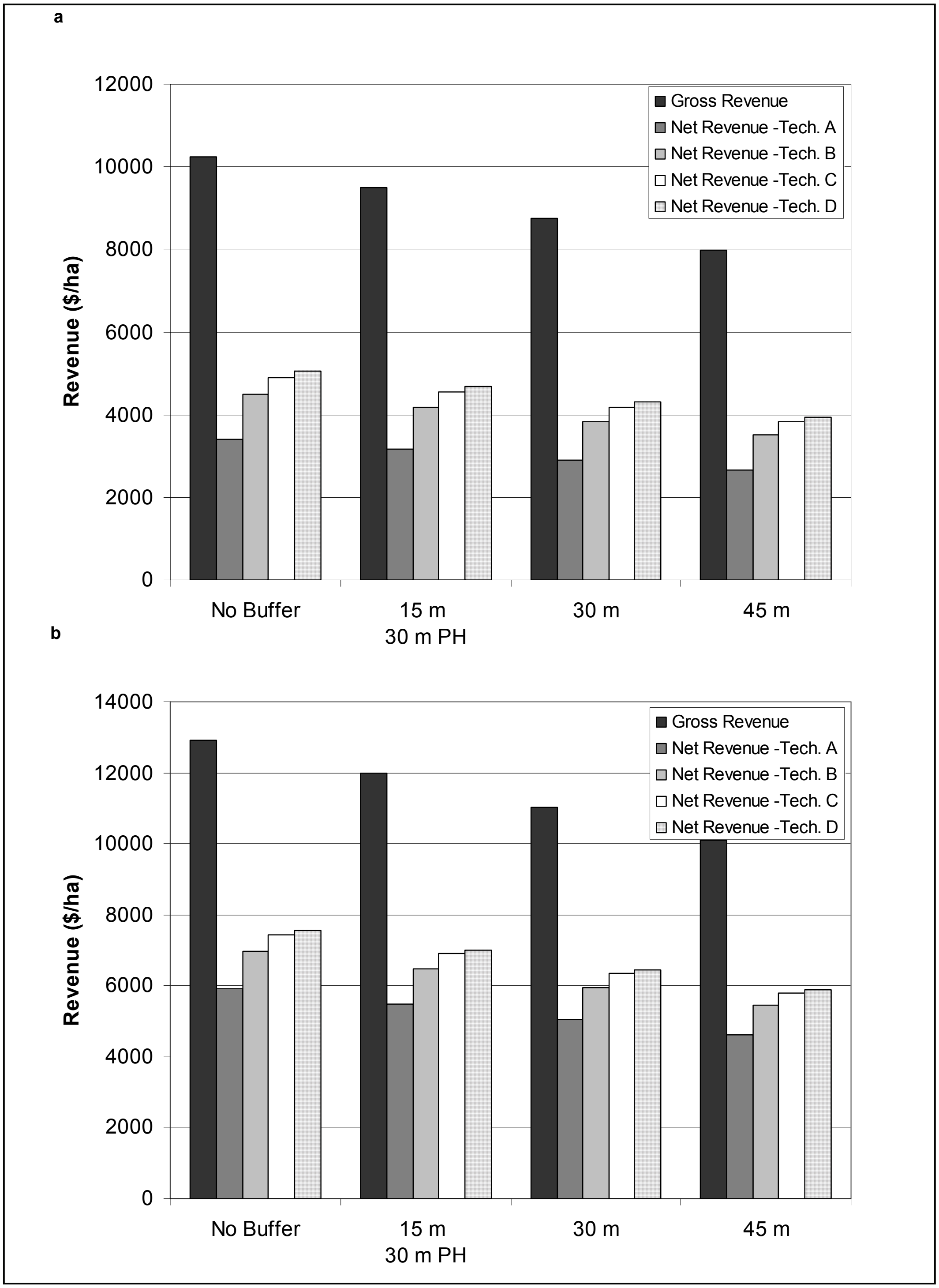

Figure 3.—Gross and net revenues for different levels of SMZ protection for (a) yellow-poplar and (b) mixed hardwood stands under the four harvesting technologies (PH=partial harvest, see Table 2 for description of technologies used) (from LeDoux and Wilkerson 2006).

Table 3.—SMZ protection scores, capital recovery costs, and benefit/cost (B/C) ratio by logging technology and stand type (from LeDoux and Wilkerson 2007)

	Yellow-poplar		Mixed Hardwood	
SMZ Protection Score	Capital Recovery Cost	B/C Ratio	Capital Recovery Cost	B/C Ratio
- - - %- - -	- -$/ha/yr- -		- -$/ha/yr- -	
		Technology A		
0	0.00	0.00	0.00	0.00
60	10.18	5.89	17.44	3.44
87	20.36	4.27	34.88	2.49
100	30.54	3.27	52.32	1.91
		Technology B		
0	0.00	0.00	0.00	0.00
60	13.37	4.49	20.66	2.90
87	26.74	3.25	41.32	2.11
100	40.11	2.49	61.98	1.61
		Technology C		
0	0.00	0.00	0.00	0.00
60	14.55	4.12	22.04	2.72
87	29.10	2.99	44.08	1.97
100	43.65	2.29	66.12	1.51
		Technology D		
0	0.00	0.00	0.00	0.00
60	14.95	4.01	22.34	2.69
87	29.90	2.91	44.68	1.95
100	44.85	2.23	67.02	1.49

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MODELING LANDOWNER BEHAVIOR REGARDING FOREST CERTIFICATION

David C. Mercker and Donald G. Hodges[1]

Abstract.—Nonindustrial private forest owners in western Tennessee were surveyed to assess their awareness, acceptance, and perceived benefits of forest certification. More than 80 percent of the landowners indicated a willingness to consider certification for their lands. A model was created to explain landowner behavior regarding their willingness to consider certification. Landowners who would consider certifying their forest would do so to satisfy both their monetary and non-monetary utility. They felt very strongly that certification would improve forest management and that it would reduce the need for regulation. They also were more likely to consider certification if they had previously received advice about forestry.

INTRODUCTION

Most consumers are vaguely familiar with the concept of an objective third party certifying products to assure a high standard, or consistency, in product quality. The certification label that is affixed to electrical appliances by the Underwriters Laboratory, thereby assuring that appliances meet or exceed standards of quality and safety, is an example (Maser and Smith 2001). The USDA Certified Organic label associated with certain fruits and vegetables at grocery stores is another, as are Quality Beef and Quality Pork Assurance Programs. Certification has evolved in a number of industrial sectors, including automobiles, chemicals, footwear, apparel, and fisheries (Sasser 2001). These sectors are often certified under the International Standards Organization with the ISO-system.

Forest certification is a relatively new development and does not deal with the product. Instead it addresses the practice of forestry, the growth and harvesting of trees, and the ecological impact after the trees have been removed from the site (Klingberg 2003). Traditionally there have been few calls for certifying forests, but that situation is changing. Forest certification is now gaining widespread attention from a variety of stakeholders, including environmentalists, policy makers, professional foresters, social activists, loggers, and the public (Viana and others 1996, Mater 1999).

Forest certification in the United States is in a somewhat unusual position when compared to the global picture because a large percentage of total forest area in the United States is under nonindustrial private forest (NIPF) ownership. In 2003, more than 10.3 million NIPF landowners in the U.S. controlled 42 percent (262 million acres) of the nation's forests. The largest portion of the nation's forest lands are located east of the Mississippi River, where 88 percent of all NIPF owners are located (Butler and Leatherberry 2004). Even more significant is the strong regional identity of the 13 southeastern states. NIPF landowners in this region number 5 million and control 89 percent of the forest area (Wear and Greis 2002). Further, nearly 60 percent of the nation's timber is produced by these 13 states, with a striking 18 percent of the world's industrial timber products originating from the South (Prestemon and Abt 2002). Wood production in the Southeast is expected to increase by more than 50 percent between 1995 and 2040, or an average of 1.6 percent per year (Prestemon and Abt 2002, Wear and Greis 2002).

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The timber resources of the southeastern region of the United States are clearly essential to both regional and global economies. Prestemon and Abt (2002) project for the foreseeable future this region will retain the distinction as the single largest producer of timber products in the world. These lands are principally owned, controlled, managed, purchased, and sold by NIPF landowners. How will this important group fit into the forest certification arena?

NIPFs are particularly important in Tennessee, where they comprise 79 percent of the state's 14.4 million acres. Moreover, these forests contribute more than 84 percent of the State's annual hardwood removal volume (Schweitzer 2000). NIPFs are also vital for the protection of the state's soil, water, and wildlife resources and for the production of non-timber goods and services.

OBJECTIVES

Some stakeholders are beginning to debate the necessity of implementing forest certification on NIPFs. If NIPF landowners are to participate in certification, a better understanding of forest landowner behavior regarding certification is needed. This study was designed to model 12 variables that could be related to landowners' willingness to consider certification.

STUDY AREA

The study focuses on West Tennessee and looks at nine counties within the 18-county U.S. Forest Service's Forest Inventory and Analysis West Tennessee Region. The nine counties were selected as they represent 70 percent of the total forest area in the region (Schweitzer 2000). Three counties were randomly selected from the list of nine for survey purposes: Carroll, Hardeman, and Weakley Counties. The three counties contain 564,300 acres of total forest land (223,369 hectares).

METHODS

Landowners were surveyed with a mail questionnaire following Dillman (2000). The original database of landowners was obtained from the Tennessee State Division of Property Assessment. Only landowners controlling 40 acres or more of forest land were targeted. A 50-percent random sample was drawn from the landowner list for the three counties. Duplicates, trusts, businesses, partnerships, sawmills, and pulp mills were removed, eliminating 77 names and resulting in a potential sample of 1,153 landowners (Carroll County 413, Hardeman County 546, and Weakley County 194). The number of landowners sampled in each county was proportional to each county's contribution to the total number of landowners in the survey.

A draft version of the survey questionnaire was developed and pretested. Landowners were assured that the information would be kept confidential. One hundred and three of the individuals were omitted (25 indicated they did not own forest land, 26 owned less than the required 40-acre minimum, 12 were deceased, one was out of the country, one was not mentally capable, six had sold their land, and 32 were undeliverable as addressed). These exclusions brought the number of surveys mailed to 1,050. A total of 532 individuals returned questionnaires for a response rate of 50.7 percent.

Telephone surveys were conducted to test for nonresponse bias. Data for the following variables were collected: size and tenure of ownership, harvest history, familiarity with certification, occupation, and age. Using the Wilcoxon rank sum two-sample test, we found that none of the variables for the nonrespondents showed a significant difference between the respondents (α=0.05).

With this project 12 variables were identified, each falling within one of three vectors: sociodemographics, monetary utility, and nonmonetary utility. The general model for landowner behavior regarding forest certification is described as,

$$Y = f\ (D, M, N)$$

where,

Y represents NIPF landowner willingness to consider forest certification;

D represents the sociodemographics vector and is further delineated by the variables: SI = size of forest ownership, YR = years of forest ownership, AD = had the landowner received advice about forest land, UP = importance of landowner staying up to date with new forestry practices and programs, ED = owner's level of education, and AG = age of owner.

M represents the monetary utility vector and is further delineated by the variables: IP = certification will increase my profits from tree farming, LR = certification will lessen the need for forestry regulation, and NT = certification will be necessary for the U.S. timber growers to compete in the international market.

N represents the nonmonetary utility vector and is further delineated by the variables: IM = certification will improve forest management, SC = certification will satisfy consumers that their wood purchases are supporting good forestry, and GR = certification will give recognition for the good forestry that is already being practiced.

The variable AD was the only dichotomous variable. The variables UP, ED, and AG were ordinal scale. The remaining eight variables were interval scale.

RESULTS

Participants were given the following definition of certification, then were asked a binary (yes/no) question of whether they would be willing to consider certification:

"Forest certification means that forests are managed in a sustainable manner and that trees are harvested with environmentally sound practices. These management practices are certified by objective third parties. Landowner participation is voluntary."

Eighty-one percent indicated "yes" they would consider certifying their forest. Willingness to consider certification became the dependent variable in the model. The model then attempted to evaluate a landowner's willingness to certify based on characteristics of sociodemographics, and on monetary and nonmonetary utility about what they believed certification would accomplish.

Model

The experimental model in this study is specified as:

$$CERTIFY = \beta o + \beta_1 SI + \beta_2 YR + \beta_3 AD + \beta_4 UP + \beta_5 ED + \beta_6 AG + \beta_7 IP + \beta_8 LR + \beta_9 NT + \beta_{10} IM + \beta_{11} SC + \beta_{12} GR + \varepsilon,$$

Table 1.—Analysis of maximum likelihood estimates for the full model

Parameter	PR > ChiSq	Odds Ratio
Intercept	0.018	0.002
IM	0.007	4.112
IP	0.162	0.365
SC	0.888	0.923
LR	0.016	3.242
GR	0.964	1.033
NT	0.487	1.399
SI	0.858	1.000
YR	0.963	1.001
AD	0.109	2.950
UP	0.049	2.005
ED	0.104	1.453
AG	0.408	0.970

where βs are model coefficients and ε is the error term. CERTIFY was the dependent variable in the model and consisted of those participants that had indicated “yes” to willingness to consider certification.

Model Estimation

The logit form of probability is preferred when analyzing dichotomous (binary) dependent variables (Menard 2000). The probabilities for logistic regression outcomes are thus specified as:

$$\Pr ob(\mathrm{Y} = j) = \mathrm{P}_i = \frac{e^{\mathrm{B}_j \mathrm{X}_i}}{1 + \sum_{k=1}^{J} e^{\mathrm{B}_j \mathrm{X}_i}} \quad j = 1,2,\ldots,J \text{ for } j = 1,2,\ldots,J$$

$$\Pr ob(\mathrm{Y} = 0) = 1 - \mathrm{P} = \frac{1}{1 + \sum_{k=1}^{J} e^{\mathrm{B}'_k \mathrm{X}_i}}$$

This can be simplified as:

$$\log \frac{\mathrm{P}_i}{1 - \mathrm{P}_i} = a + Bi\mathrm{X}_\mathrm{i}$$

where: P_i = probability that a particular action will be made; $\mathrm{B}i$ = model coefficients.

A test with the full model (retaining all 12 variables), was conducted to assess the odds ratio for individual variables. Initially this analysis revealed nine variables that met the minimum odds ratio requirement of ≥1.0 (Table 1). The remaining three variables (dummy set) were eliminated from the model. Follow-up iterations were conducted, eliminating variables not meeting the odds ratio minimum requirement of ≥1.0 until only six variables remained (IM, LR, SI, AD, UP, and ED). Further reductions in the model eliminated variables with the highest chi-square values that exceeded the significance (α = 0.05)

Table 2.—Analysis of maximum likelihood estimates for the reduced model

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr >ChiSq	Odds Ratio
Intercept	1	-5.049	1.180	18.319	<.0001	0.006
IM	1	1.223	0.300	16.623	<.0001	3.396
LR	1	0.699	0.246	8.095	0.0044	2.012
AD	1	1.171	0.465	6.347	0.0118	3.224

requirement. The variables remaining following these reductions were IM, LR, and AD (Table 2). The model was reduced to:

CERTIFY = -5.049 + 1.2227IM + 0.6994LR + 1.1705UP
where,

IM = certification will improve forest management,
LR = certification will lessen the need for forestry regulation, and
AD = had the landowner received advice about his or her forest land ($\tilde{R}^2$ = .3722).

DISCUSSION

The regression model was significant at $\alpha = 0.05$, with the highest chi-square value of the three independent variables being 0.0118. Variables in the final model represented each of the three vectors. The sociodemographics vector (D) was represented by independent variable AD (had the landowner received advice about their forest land); the monetary vector (M) was represented by independent variable IM (certification will improve forest management); and the nonmonetary vector (N) was represented by LR (certification will lessen the need for forestry regulation).

Landowners who would consider forest certification sincerely felt that certification would improve forest management. With an odds ratio of 3.396, this independent variable carried considerable explanatory power and was of highest importance to the participants.

One of the most interesting results was that landowners felt strongly that certification would lessen the need for forestry regulation. This variable was placed into the monetary vector because regulations most generally seek to place restrictions on harvesting or other profit-motive land uses. Apparently landowners in the study area have some concern over this issue, enough that this variable had more explanatory power than 10 others.

Only one of the six demographic variables tested (AD) was strong enough to retain in the model. Having previously received advice or information about their forest land was a strong determinant for willingness to certify.

CONCLUSION

This model confirms the conclusion of Newsome and others (2001) that landowners rate monetary and nonmonetary reasoning for certification nearly equally important. Landowners who would consider certifying their forest would do so to satisfy both their monetary and nonmonetary utility. They felt very strongly that certification would improve forest management and that it would decrease the need for forestry regulation. They were more likely to consider certification if they had previously received advice about forestry.

The three predictor variables in the model offer some insight into landowner concerns and motives. Landowners were more likely to consider certification if it would improve forest management or lessen the need for forestry regulation. Exactly how it might improve forest management or affect regulation was not clear. Follow-up research is needed to elucidate landowner concerns over these issues.

Landowners receive information and advice regarding their forest land for a number of reasons and through a number of sources. The state division of forestry and consulting foresters were the two most common sources of forestry advice. However, 91 percent of the respondents were either not at all or only a little familiar with certification, a finding that suggests a large information gap. Perhaps the professional foresters providing the advice are not advocating or suggesting certification; perhaps they are not aware (or even aware) of the benefits and the process. Before forest certification can expand on any measurable scale, state foresters and professional consulting foresters must be better informed and involved in information dissemination.

To date, there has been limited research on private landowners and forest certification. This important and sizable ownership category should be given more serious attention as certification momentum continues to build, especially considering how important NIPFs are to regional timber supplies. The model created by this study explains a portion of landowner behavior regarding willingness to consider forest certification. Future research should focus on methods of transforming landowner willingness to certify into actual certifications and indentificaqtion of the factors most influential in this decision.

Finally, landowner costs of entering certification were omitted from the study because it has been determined that few would pay for certification and that it should be free (Vlosky 2000, Newsome 2001). A comprehensive plan that suggests how to operationalize free or low-cost forest certification on NIPF lands on a much broader scale should be examined.

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LANDOWNER ATTITUDES AND PERCEPTIONS OF FOREST AND WILDLIFE MANAGEMENT IN RURAL NORTHERN MISSOURI

Brian E. Schweiss and John Dwyer[1]

Abstract.—Improving Missouri's forest lands depend on private landowners. Cluster analysis was used to combine nonindustrial private forest landowners with similar interests based on attitudinal information gathered from a mail questionnaire to forest landowners in Macon County, MO. Clusters were analyzed based on objective data gathered in the questionnaire. Seven types of forest landowners were identified: absentee hunter, agrarian/steward, residential landowner, agrarian/economic, wildlife manager, uncertain landowner, and next generation landowner. Outreach efforts are discussed relative to potential impact and use of various methods for each of the seven clusters.

INTRODUCTION

Private forest lands are held by a diverse array of landowners. The Missouri Department of Conservation (MDC) offers technical assistance to landowners for a variety of natural resource management activities, including forest and wildlife management. Requests for timber sale assistance and guidance regarding woodland and wildlife habitat improvement are not uncommon, but in reality they involve only a small percentage of the forest landowner population. Numerous studies in other states have revealed similar situations (Arano and others 2002, Egan and others 1993, Clark and others 1992, Rom and others 1990).

OBJECTIVES

This study was designed to update and refine natural resource managers' understanding of forest landowners, including their knowledge of and willingness to implement a variety of forest and wildlife management activities. Willingness to adopt management practices will be examined from the perspective of a landowner motivational typology (Fairweather 1979, Greene and Blatner 1986, Kurtilla and others 2001, Kendra and Hull 2005, and Lewis 1979). The landowner motivational typology entails describing the landowner respondents, as they are grouped into clusters based on their responses to a series of attitudinal survey questions. Their responses may reveal motivational characteristics, which become the cornerstones for identifying groups of landowners with similar motivations and possibly land management styles. Groups of forest landowners are further described based upon their land management practices and interests, including landowner propensities for resource management (Kurtz and others 1984).

A deeper understanding of what motivates landowners with regard to their forest resources is needed in order to develop better outreach programs and more appropriate outreach products. To learn more about forest landowners, we undertook a study designed to: 1) delineate groups of landowners based upon attitudinal data regarding motivations for and interest in land ownership; 2) gauge the interest in and willingness among the groups to implement forest and wildlife management practices; and 3) compare the groups regarding interest in and methods of conducting a timber sale.

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STUDY AREA

The study area consisted of Macon County, MO, located in the north-central part of the state. According to the U.S. Census Bureau, Macon County had 15,762 residents in 2000. The city of Macon is the largest town and the county seat with a population of 5,538. The next largest town in Macon County is Bevier, with a population of 723.

Macon County consists of 538,745 acres. Dominant land uses include cropland (25.7 percent), grassland (51.6 percent), and forest land (20.1 percent). The remaining areas are open water (1.4 percent) and other areas such as roads and other impervious materials (1.2 percent) (MORAP 16 Class Land Cover Map: 1982). Of the forested land, 89.5 percent is held by private non-industrial landowners. Forests are frequently neglected and cut over. Threats to the resource include cattle grazing in the woodlands, land clearing, and lack of professional forest management which often leads to over-harvesting and high-grading.

Settlement of the area occurred in the mid-1800s. Before Euro-American settlers arrived, open prairie and savannas, along with upland and bottomland forests and woodlands were present. Nigh and Schroeder (2002) divide the county into two ecological subsections: the Chariton River Hills subsection lying west of U.S. Highway 63 and the Claypan Till Plains subsection lying east of US Highway 63. Highway 63 divides the county roughly in half.

The Chariton River Hills is characterized historically as a mosaic of prairie, savanna, and woodland and forest. The topography consists of rolling hills with narrow ridges and valleys. Within the Claypan Till Plains, the topography is much different. The landscape is much flatter, with rolling hills near streams and drainages. As the name implies, it has well developed claypan soils. Presettlement vegetation was largely prairie with narrow belts of timber along the streams (Nigh and Schroeder 2002).

Following settlement, much of the woodlands and forests were cleared and the landscape was converted to pastureland and cropland. In the southwest part of the county, coal mining prevailed. This enterprise began as small shaft mines run more locally but evolved into larger strip mines that reshaped the topography of a significant component of the area. The Macon County Soil Survey indicates that 1.3 percent of the county is in a soil type that was derived from surface mining (USDA Soil Conserv. Serv. 1995).

Currently, the local economy depends largely on agriculture, which consists of row crop farming of soybeans, corn, wheat, and sorghum. Macon County is home to one ethanol plant. Livestock production, mainly cattle and hogs, is also prominent. Coal mining ceased in the early 1990s.

METHODS

Sampling Design

The landowner database for this study was developed at the county level. It focused on 475,498 acres of privately owned land in Macon County. This acreage excludes all state-owned lands, lands leased for public use by the state, and lands within any incorporated areas.

To be included in this study, private landowners had to own at least 20 acres of forest cover. Parcels could include individual ownerships, partnerships, and clubs or organization-owned lands.

The common land unit (CLU) data layer developed by the USDA Farm Services Agency was used to identify landowners with 20 or more acres of forest land. This data layer outlined landowner boundaries as they fell into the following categories: forest cover, residential, impervious areas, and other open acres such as cropland and pasture.

ArcMap 3.2 and 8.1 (Environmental Systems Research Institute, Redlands, CA) were used to determine all acreages and to refine the CLU data layer. Each polygon has an identifying farm number, from which an ownership data layer was developed. In addition, forest land cover was identified by farm number and acreages summarized to determine which ones met the minimum acreage criteria.

Parcels were identified using the Macon County 2002 Plat Book. A landowner address list was obtained from the county courthouse in May of 2003. Names were matched to the ArcMap database and addresses were entered. The final data layer consisted of 1,368 usable addresses. Landowners in the study owned 343,808, acres or 63.8 percent of the eligible land area.

Survey Design

The survey was administered by mail following methodology outlined by Dillman (2000). The survey was designed to gather two basic kinds of information: 1) subjective elements - motivational and attitudinal assessments regarding reasons for land ownership, ecological perspectives, economic intentions, quality of life, and social orientation; and 2) objective information of two types: pure objective demographics and other landowner attributes, and landowner reports on past and intended management practices and sources of information. The typology is to be constructed exclusively on the basis of the first subjective information. Types are further described in relation to the second objective set of measures.

Attitudinal/motivational information was gathered using a series of statements. Statements included a range of interest in each topic (Hickman and Gelhausen 1981). Respondent interest in the topics was measured based upon their level of agreement with statements using a 5-point Likert scale. The evaluative categories of strongly disagree, disagree, undecided, agree, and strongly agree were used. In other instances, it was more appropriate to use a similar scale based on importance rather than agreement. Objective demographic data gathered were either ordinal or categorical.

Typology Establishment

Cluster analysis was used to analyze the data and develop the landowner typology. The raw scores from the surveys were used for 48 attitudinal statements in a hierarchical agglomerative method. This method assumes that each case initially defines a separate cluster and then merges cases into larger clusters. The Wards Method, within the statistical software program SAS 8.02 (SAS Institute, Inc., Cary, NC), was used to identify these larger clusters.

All of the variables for each record that are used in cluster analysis must have a completed response. Of the 753 surveys that were returned, 521 surveys had 100 percent of the clustering variables completed. An additional 83 surveys were missing only one of the 48 variables. Logistic regression was used to help salvage the 83 surveys that were missing one variable (Lohr 1999).

The number of clusters was determined by examining the semi-partial R^2 and the squared multiple correlation, R^2. The semi-partial R^2 represents the decrease of variability explained between one cluster

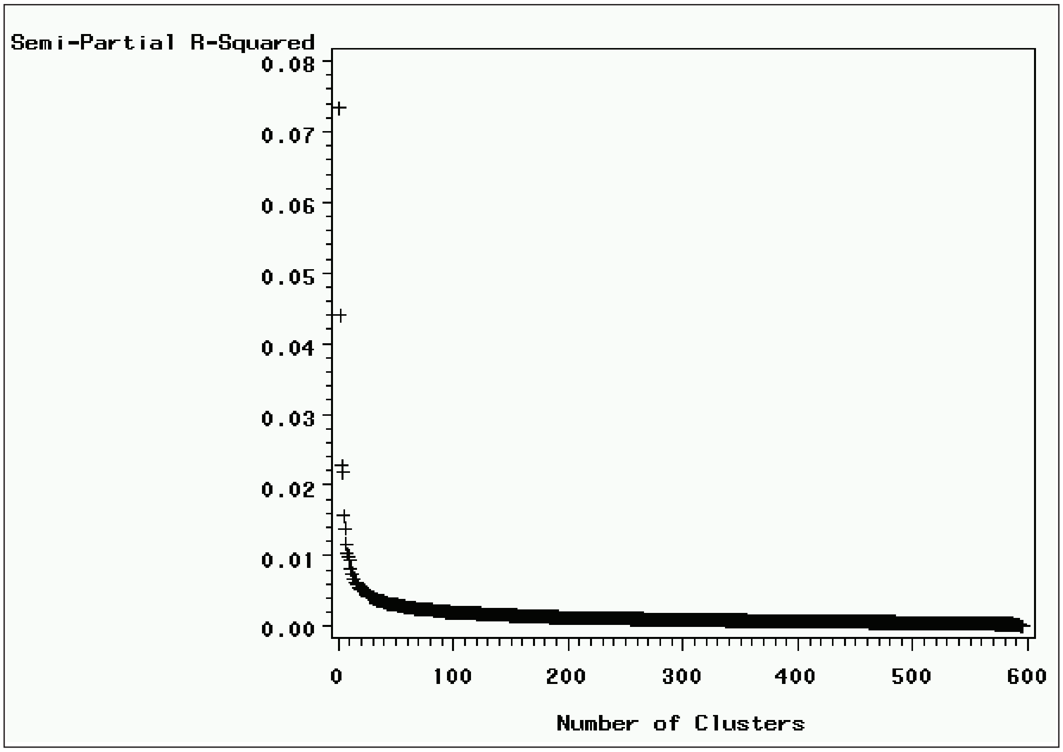

Figure 1.—Graph of semi-partial R^2 and number of clusters.

and the next subsequent cluster. R^2 represents the proportion of the variability accounted for by each subsequent cluster. The goal of this method is to generate the largest R^2 value for the fewest number of clusters possible as determined in conjunction with the decrease in variance explained in the semi-partial R^2 from one cluster to the next (SAS 8.02 online documentation).

Subsequent clusters were analyzed with ANOVA and LSD test in SAS 8.02 to determine if significant differences were present between clusters for all possible pairs in terms of the 48 subjective variables. Clusters were further described based on objective information provided in the survey. Such information included land uses, owner demographics, and residence, along with self reports of landowner forest and wildlife management interests. Statistical tests used were Pierson's Chi Square, the Monte Carlo Estimate of the Exact Test, and ANOVA. A 0.05-level of significance was used for all tests.

RESULTS

The first mailing yielded 1,312 viable addresses. Of this, 753 (57-percent response rate) surveys were returned and 596 (45-percent response rate) surveys were used in the clustering procedure and subsequent analysis. Among the 596 surveys were those that were 100 percent completed and the ones with a single calculated variable.

Seven clusters were chosen based upon guidelines outlined in the methods section. Within Figure 1, each "+" symbol represents where one cluster was joined with another. The distance between the joins indicates the amount of variability explained in the Semi-Partial R^2. Seven clusters were chosen since at this stage, the amount of variability explained becomes negligible as we move down the graph towards higher subsequent clusters.

Significant differences were found for the seven clusters at the .05 level of significance for 45 of the variables. In descriptions of differences, terms used such as “highest” and “lowest” are significant for that cluster described below. Other statements, such as mixed views, high, low, or fair, are more general in nature and did not demonstrate uniqueness of one type but reflected a trend or inclination in attitudes between groups for various statements. In addition, significance was determined for many of the land management practices and demographics as described in the next section.

Landowner Groups

Absentee Hunter (n=92)—The “Absentee Hunter” used the property mainly for turkey and deer hunting while residing elsewhere. Only 9 percent of respondents live on the property, but many more value the privacy and solitude their forest offers. They also have one of the largest proportions (36 percent) who would rather live in a larger urban area and commute as needed to the land, and 56 percent have little connection to the area via friends and family. The average size of landholding is 191 acres, much of it in forest and grassland. Income from the land is not a priority, but some respondents do receive income from various sources with conservative reserve program (CRP) being most popular. The most popular management practice is putting in food plots. Woodlands are an important part of their land, but Absentee Hunters are the group most likely to leave the forest alone and not have a timber sale. Approximately 69 percent of the respondents have some education beyond high school. This group has the highest proportion of members earning the most income, with 66 percent earning more than $65,000 per year.

Agrarian/Steward (n=104)—Members of this group reside on the property and uses it mainly for agricultural operations but desires to manage for certain wildlife species. This group prefers to live on the land. Members value rural living and the privacy and solitude the land offers. They have spent most of their lives in rural areas. Income generation from the land is important for 87 percent of respondents, and 64 percent are farmers. Land income makes up close to one-third of their annual income. This cluster, along with the Wildlife Manager respondents, had the greatest interest in timber as an investment, but still only 29 percent of respondents expressed this view. Members have a high interest in actively managing their woodlands; 51 percent have done some woodland management for wildlife and 28 percent have done timber stand improvement. In addition, they have the highest rate of timber sales with 30 percent having had at least one in the past 5 years. They are the largest owners of land with an average of 395 acres, and the dominant uses are grassland and cropland. They expressed a desire to leave the property to their children. While 69 percent hunt deer, most do not express a desire to see more deer.

Residential Landowners (n=90)—This group likely resides on the property and uses it as a primary residence and recreation with little interest in income from the land. Members of this cluster had the smallest average landholdings. Land size averaged 98 acres and the dominant uses were forest and grassland. They value living on the land and those who do not live within 49 miles of the land. They appear to own land for a primary residence or close piece of recreational property but do not desire income from the land. Hunting is important for 94 percent of respondents. They are the highest full-time employed group at 69 percent and only 13 percent claim to be farmers. They like to help wildlife. They have done some wildlife management, such as timber stand improvement (28 percent), improving woodlands for wildlife (67 percent), and planting trees and shrubs for wildlife (45 percent). Numerous respondents hunt deer and turkey. They also enjoy nonhunting activities such as wildlife viewing and picking nuts, mushrooms, or berries.

Agrarian/Economic (n=140)—The land is viewed as a source of income through agricultural operations, and respondents have a low interest in wildlife and wildlife management. Farmers make up 73 percent of the members in this group. Common income sources are sale of crops, cattle, and hay. The sale of timber as a source of income is second highest, 23 percent have had a timber sale in the past 5 years. A small percentage of respondents indicate doing past timber management such as timber stand improvement. A higher proportion of respondents seems inclined towards clearing the land if it were economically feasible. The group values living on the land and 69 percent of respondents reside on the property. More than two-thirds of those who do not live on the land live within 49 miles of it. They value rural living and 92 percent have spent most of their lives in rural areas. Keeping the property in the family is important.

As a group, they do not believe wildlife needs help. Members value hunting, but not as strongly as do the three clusters discussed above or the Wildlife Manager cluster discussed next. They also value nonhunting recreation less than do the previous mentioned clusters. They are more likely to agree that wildlife is frequently a nuisance on their land. The Farm Services Agency is the most commonly used source of assistance for the type (62 percent). Membership is highest for the Farm Bureau at 20 percent. Out of all the clusters, this group is most inclined to do as they see fit with their land despite what others might say.

Wildlife Manager (n=67)—Members express some of the greatest interests of any group for hunting and wildlife management. All respondents indicated they value owning land on which to hunt and fish. Respondents also like to help wildlife (99 percent) and believe wildlife needs assistance (75 percent). They have the highest rates of implementation of wildlife management practices, such as food plots, planting trees, managing grassland for quail, and improving woodlands for wildlife. In fact, 100 percent of respondents indicate it is “somewhat likely” or “very likely” they will improve woodlands for wildlife in the next 5 years.

The highest percentage of deer hunters and turkey hunters along with trophy buck hunters are represented in this type. They also enjoy other recreational activities such as wildlife viewing, and picking nuts, mushrooms, and berries. Members agree or strongly agree (90 percent) that some government involvement is needed to protect the environment. They also utilize MDC cost-share assistance the most (18 percent indicate using it in the past 5 years). They value living on the land, but only 56 percent do. Fifty-two percent have some education after high school and 47 percent earn $25,000 – $64,999 annually; 36 percent earn greater than $65,000 annually. Sixty-seven percent of the members work full time.

Uncertain Landowner (n=59)—This category tends to have few strong opinions about the land and is generally not interested in wildlife or its management. In response to many of the motivational and attitudinal questions, respondents in this group tend not to respond as strongly agree or disagree, but more as simply agree, disagree, or are undecided. Living on the land, land to relax and enjoy, or land to hunt and fish on are expressed as important by many respondents. However, close to one-third (32 percent) do not value the land for hunting and fishing and more than one-fourth (27 percent) do not express a strong interest in privacy and solitude. The cluster is split with regard to income generation and keeping land in the family. They have a lower desire to leave the property to their children or heirs, with only 46 percent expressing a desire to do so. The potential for land to be sold in the next 5 years is highest for this group; 39 percent indicated it is “somewhat likely” to “very likely”. About two-thirds express interest in helping wildlife, but they do very little wildlife management. They own mostly grassland and forest land.

Table 1.—Summary statistics describing the land use distribution by cluster

Cluster[a]	AH	A/S	RL	A/E	WM	UL	NGL	Pr.>F ANOVA
n	92	104	90	140	67	59	44	
Percent of respondents	15	17	15	23	11	10	8	
Mean crop (acres)	24	121	4	104	22	19	107	0.0001
Mean grass (acres)	60	140	29	144	55	52	83	0.0001
Mean forest (acres)	87	95	58	67	72	51	51	0.281
Other (acres)	4	21	3	13	10	7	14	0.1315
Total (acres)	191	395	98	352	171	135	274	0.0001

[a]AH = Absentee Hunter; A/S = Agrarian Steward; RL = Residential Landowner; A/E = Agrarian Economic; WM = Wildlife Managers; UL = Uncertain Landowner; NGL = Next Generation Landowner

Respondents also indicated they did not get to interact with their neighbors too often. Use of information sources is the lowest of all clusters. Half of respondents are fully or semi-retired and only 38 percent are working full time. They are the oldest respondents, along with those in the Next Generation Landowner cluster. The highest percentage of respondents earns less than $25,000 annually (35 percent) and the lowest percentage earns more than $65,000 (16 percent). One additional item to note: 25 percent of the respondents inherited the land.

<u>Next Generation Landowner (n=44)</u>—The desire to keep property in the family rates high for this type. Acquiring land through inheritance is highest for this cluster at 44 percent. They do not have a rural living preference and do not value as strongly as other groups the rural lifestyle attributes such as land for privacy and solitude. Management of the forest and open-land resources for wildlife or timber is low compared to other groups. Only 58 percent of respondents have lived most of their lives in rural areas and only 40 percent currently live in rural areas; only 13 percent live on the land. Those who do not live on the land are fairly well distributed from less than 49 miles away to more than 100 miles away. This group also has the second highest percentage of respondents earning more than $65,000 income annually (46 percent). Income from the land is not as strong a motivation factor as for the Agrarian clusters but respondents do have several noteworthy income sources. Share-cropping income and CRP income are high when compared to other types, along with some row crop income. Respondents did express interest in helping wildlife, yet implementation of wildlife management practices is low compared to other clusters.

Landowner types are further described in Table 1 including size of clusters and acreages of the three dominant cover types. The Agrarian types have the largest proportion of members with 23 percent as economic respondents and 17 percent as stewards. The lowest membership was found in the Next Generation Landowner type with 8 percent of the respondents. Both crop acres and grass acres were significantly different between types; Agrarian and Next Generation types have the largest average landholdings. The forest cover was not significantly different between types, suggesting that forest land is not actively sought after by one group or another but is more a byproduct of the landscape.

Sources of Information

Information sources were investigated to determine some of the best possible avenues for reaching forest landowners in the area. These resources included the *Missouri Conservationist* magazine, Farm Services Agency, Natural Resources Conservation Service, Missouri Department of Conservation, and Internet web sites. The following draws attention to the groups that use these sources the most. The *Missouri Conservationist* magazine was very popular with the Wildlife Managers; 85 percent receive it. It is also popular with the Absentee Hunter (64 percent), Agrarian/Steward (69 percent), and the Residential Landowner (63 percent). The Farm Services Agency is used by 62 percent of the Agrarian/Stewards and Economic respondents, and 60 percent of the Next Generation Landowners. The Natural Resources Conservation Service shows much less use with 48 percent of the Agrarian/Steward members and 36 percent of the Wildlife Manager members. The Missouri Department of Conservation is used by 67 percent of the Wildlife Manager respondents, then in decreasing popularity by the Residential Landowner (56 percent), Absentee Hunter (52 percent) and the Agrarian/Steward (51 percent). Internet web sites were most popular with the Wildlife Managers at 42 percent, then with the Absentee Hunter members at 29 percent. The Uncertain Landowner group was not mentioned since in all these instances they use the information sources the least.

DISCUSSION

Discussion of Clusters

Several characteristics differentiate the groups found in this study. Most notable are economic intentions, wildlife orientation, rural living lifestyle preferences, and to a lesser extent, orientation toward government involvement, and legacy. The Agrarian clusters have the strongest economic motivation as it relates to their land, whereas the Absentee Hunter and Wildlife Managers have some of the strongest wildlife orientations. Concepts of legacy such as leaving property to one's children or improving it for the next generation can be seen throughout many of the types, but the Uncertain Landowner appears to have the least interest in legacy or leaving property to offspring.

Practical Implications

It is important to note that resource professionals are reaching landowners and likely have more requests for assistance than they can complete in a reasonable time frame. In addition, funding allocated to wildlife and forest management assistance is quickly spent. Many of the information sources, especially one of the most popular, the *Missouri Conservationist* magazine, contain articles and tips on forest and wildlife management. However, landscape-level goals such as increased quail numbers, and managed forest resources are difficult to attain. In many cases, outreach sources are good at reaching interested and consuming audiences, or in other words, landowners who actively seek educational or technical assistance, in this case, the Absentee Hunter, Residential Landowner, and Wildlife Manager cluster members. However, a successful landscape-level program must also reach a nonconsuming audience, or those who express little interest in educational and technical assistance.

Educational events such as peer-to-peer learning and field days have greater potential than any cost-share or other financial incentives. Incentives show great promise in meeting needs of landowners interested in intensive management but not those who are more casual. Thus, this typology of forest landowners demonstrates effectively that educational articles, services, and assistance are very appealing to specific groups. Viewing the goals and attitudes of nonconsuming audiences or those who do not actively seek out information, and marketing services to them that meet their goals and that of state and federal agencies is a vital use of these typologies. For instance, peer-to-peer events could demonstrate to Agrarian/Economic members how forest and wildlife management can be blended into their agricultural operations without infringing upon the members' desires to farm or raise cattle. Evaluating potential effectiveness of new initiatives and incentive programs for the various groups is another opportunity.

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SUSTAINABLE BIOENERGY PRODUCTION FROM MISSOURI'S OZARK FORESTS

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Abstract.—The main source of wood fiber for energy resides in Missouri's forests. Alternative bioenergy systems that can use forest thinning residues are electrical energy, thermal energy, and liquid bio-fuel. By applying a thinning rule and accounting for wood fiber that could go into higher value wood products to all live biomass data extracted from the U.S. Forest Service Forest Inventory and Analysis database for a 44-county area in southern Missouri, we determined that a "typical" Ozark upland hardwood acre would conservatively yield 9.3 green tons as a result of a forest thinning operation. This per-acre yield was then spatially distributed across privately owned land across the selected area based upon the deciduous cover layer in the Missouri Resource Analysis Project database. Based on the infeed requirements of three wood-to-energy enterprises, our spatial analysis tool revealed that to support a sustainable re-entry interval of 20 years, thinning operations would need to be conducted on one out of every 67 privately owned acres within a 45-mile radius of the bioenergy plant.

INTRODUCTION

A potential feedstock for meeting some of our nation's renewable energy goals is wood: wood waste from sawmills and secondary manufacturing plants (e.g., flooring plants and pallet mills); urban wood waste from utility rights-of-way and storm debris clean-up operations; and wood from thinning our overcrowded forests. Wood residuals from sawmills and secondary manufacturing plants (e.g., sawdust, slabs and edgings, chips) are no longer considered waste as they are going into everything from mulch to composite deck material. As a result, very little of this material is available for any large-scale wood-to-energy enterprise. Urban wood waste seems like a reasonable alternative to mill residues for producing energy, but the desirable fiber of the tree trunk is usually commingled with bark, smaller branches, and leaves. These latter components have very low energy values due to their high moisture content and they also generate larger amounts of ash.

The main source of wood fiber for energy lies in Missouri's forests. The good news is we have a lot of it. Missouri is approximately 45 million acres in size, one-third of which is forested (Moser and others 2007). The challenges are the economic viability and the biological sustainability of a wood-to-energy enterprise.

OBJECTIVE

Our objective was to determine how many forested acres would be required to supply three different types of wood-to-energy systems based upon either existing or accepted technologies given the constraints of ownership patterns and the stipulation that the wood must come from sustainable forest thinning operations.

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WOOD-BASED BIOENERGY SYSTEMS

Potential wood-based bioenergy systems include: (1) electrical energy; (2) thermal energy for heating/cooling institutional buildings or large multi-building facilities; and (3) liquid fuels (e.g., bio-oil or ethanol). Rather than board feet, cords, or green tons, the proper currency for energy systems is British Thermal Units (BTUs). One BTU is the amount of energy required to raise the temperature of 1 pound of water by 1 °Fahrenheit. Some common conversion factors to remember when converting from green tons of wood to BTUs are: (1) green wood has a moisture content of 50 percent; (2) there are 8,600 BTU per pound of dry woody biomass; and (3) there are 2,000 pounds per ton.

Electrical Energy

Depending upon time of day and time of year the load factor on the power grid can vary tremendously, but on average, 1 megawatt (MW) can meet the energy needs of around 800 homes. Approximately 3.41 million BTUs are required to produce 1 MW of electrical energy for 1 hour. Unfortunately, the technology for direct-firing power plants currently in operation is based upon coal and natural gas, both of which have higher per-unit BTU energy content than wood. As a result, burning wood in these plants captures only about 37 percent of wood's energy potential. It's like heating your home using an open fireplace.

Even though generation of electricity is not the most prudent use of wood for energy, several biopower plants are in operation today, including in Burlington, VT (50 MW), Craven County, NC (40 MW), and St. Paul, MN, (25 MW). Given the above constraints, a 25-MW power plant would require 597,432 million BTUs annually (3.41 million BTUs/hr x 24 hr/day x 365 days/yr) or 187,878 green tons of wood.

Thermal Energy

One feature of the St. Paul, MN, biopower plant is that the utility uses the low-pressure steam exiting the electrical generating turbines to heat and cool the central downtown area. This process is identical to that at Northwest Missouri State University in Maryville, MO, which has been generating low-pressure steam from wood fiber to heat and cool 2,000,000 sq. ft. of campus buildings since 1982. Sixty-six percent of the required 250,000 million BTUs come from wood chips, 10 percent from palletized, clean, community waste paper, and the remainder from natural gas. The wood chips vary from 10 to 40 percent moisture, averaging just over 30 percent. These chips are acquired from the waste generated by the forest products industry in the region served by the University. Paper pellets were introduced in 1992.

The 1980-81 Northwest Missouri heating/cooling plant capital cost valued in 2007 dollars is $7.8 million. The university has paid an average of $26.50 per ton for wood chips delivered to the plant for the last three years of record. The resulting variable cost per million BTUs of steam provided is $4 to $5 compared to nearly $11 for natural gas. Northwest Missouri has saved $475,000 per year for the last 23 years. A thermal plant of similar design to the Northwest facility would require 29,000 green tons of wood annually.

Liquid Bio-fuels

This wood-to-energy technology is still much in its infancy and is probably 2 to 5 years away from maturing into commercial-sized production facilities. As opposed to the enzymatic process of producing ethanol from corn, bio-fuels derived from wood will be driven primarily by gasification technology. Sounds high-tech, doesn't it? But anyone who has ever been involved with making charcoal is already familiar with this process. The old charcoal kiln has been replaced with a bio-reactor where temperature and atmosphere within the reactor can be tightly controlled. And instead of a focus on the lumpy, carbon residue (charcoal) left at the end of the process, the focus is now on capturing the volatile compounds that are driven out of the wood during the process. Depending upon the specific technology applied, the end product can be combustible gases, a mixture of alcohols (including ethanol), or a heavy bio-oil.

For the purpose of our discussion here, we will focus on a unique technology developed by Bioengineering Resources Inc. (BRI) of Fayetteville, AR, that combines gasification with an enzymatic reaction downstream from the gasification step to produce 6 to 8 million gallons of ethanol. This system also produces 5 to 6 MW of power. These modular units require 200,000 tons of green biomass annually.

Before conducting preliminary economic analyses on the construction and operation of these bioenergy plants, we must determine proper regional cost and revenue figures for input into the models. To obtain these inputs, we need to know how the available woody biomass is spatially distributed across the state in order to identify regions that will be able to support the facility.

WOODY BIOMASS AVAILABILITY

More than 350,000 private citizens own roughly 83 percent (12.1 million acres) of the state's 14.6 million acres of forest land (Moser and others 2007). The remaining 27 percent is owned by private businesses (10 percent) and public agencies (17 percent). The wood fiber on these lands is not considered available for bioenergy because the trees are either destined for other uses or virtually "locked-up" in regulatory statutes. Based upon personal surveys, the general consensus among forestry professionals in the state is that 90 to 95 percent of the lands owned by private individuals are not being actively managed and that only an additional 25 percent would be captured with some type of wood-to-energy market incentive.

Total tree biomass is the total weight of all-live aboveground components of forest trees. In Missouri, approximately 72 percent of a tree's total biomass is found in the stem and the remaining 28 percent is in the stump, top, and limbs (Moser and others 2007). We chose to measure biomass for bioenergy in green tons rather than BTUs because the forest products industry is more familiar with weight measure.

The first step in developing our woody biomass spatial analysis tool was to determine what the "typical" Ozark acre might yield as a result of a forest thinning operation. We took a conservative route for two reasons. First, we wanted a silvicultural prescription that would have minimal (if any) adverse effect on the existing forest products industry in the state. Plus, we wanted to leave the landowner with a residual forest capable of producing high-value timber at some point in the future. Second, we wanted to paint a solid picture of the wood supply for potential investment capital.

This "typical" acre contains some caveats. For example, it would be expected that an acre of ground with a south- or west-facing aspect would be lower in site quality and therefore yield less than an acre found on a higher quality, north- or east-facing aspect. Also, while an even-age silvicultural prescription would be the norm, local site conditions and individual ownership objectives would influence the actual biomass yields. For the first iteration of this tool, we assumed that the thinning operation would leave a residual hardwood forest stand just above the suggested basal area of 65 square feet per acre (Gingrich 1967).

We developed our acre of Ozark forest by extracting U.S. Forest Service Inventory and Analysis (FIA) data from the agency's online database and Forest Inventory MapMaker V3.0 (Miles 2001). The data were filtered based upon the following constraints:

1. All Missouri cCounties south and east of the I-44 corridor. This constraint yielded 1,800+ FIA plots and produced a seamless mosaic across county lines that otherwise would have resulted in disjoints between counties if based on a county-by-county query.
2. Land classified as "timberland": forest land not restricted from harvesting by statute, administrative regulation, or designation, and capable of growing trees at a rate of 20 ft^3 per acre per year at maximum annual increment.
3. Ownership classified as "private"; all public lands were excluded due to the uncertain nature of availability.
4. Hardwood species only; cedar, pine and mixed oak/pine were excluded due to potential biorefinery feedstock uniformity requirements.

The extracted data were stratified by diameter class and basal area (BA) class (Table 1). Gingrich (1967) found that 40 percent of the basal area could be removed from a stand that was 100-percent stocked without loss of total stand growth. Using this result as a recommendation for a maximum thinning rule, since 0-40 BA is understocked and the median of 41-80 BA is at the cut-off of a fully stocked upland hardwood stand, no thinning tonnages would be available from these acres.

We assume the median stocking level for the 80-120 BA is 100 ft^2 per acre. A 40-percent reduction by thinning would leave 60 ft^2 per acre, which would leave an under-stocked stand in most cases. To avoid this outcome, we reduced the thinning percentage to 30 percent. Because nearly all of our Ozark forest stands are beyond the point of canopy closure, we assumed that volume is linearly related to BA in stands of these diameter ranges in upland oaks. Since the 120+ BA class is open-ended, we chose to be conservative and set the average BA at 125 ft^2 per acre. We further chose a thinning target of 75 ft^2 per acre which reflects a 40-percent thinning and keeps all acres in the fully stocked class.

Then for each diameter class, we asked mill operators in the region for their opinion as to what percentage of the incoming wood could be utilized for higher-value wood products. Keep in mind that in Missouri, higher-value wood products include industrial blocking and pallets. We then totaled the amount of wood across all the diameter classes that would be potentially available for bioenergy and divided that figure by the total amount of private timberland as extracted from the FIA database to yield an average of 9.5 green tons per acre.

This quantity of available biomass was then spatially distributed over the same area of the Missouri Ozarks from which the FIA data were extracted based on the percentage of deciduous forest cover. This forest cover data layer was made available through the Missouri Resource Assessment Partnership (University of Missouri, Columbia, MO). The spatial distribution was conducted on a 30-m^2 pixel and then aggregated by square mile to frame the biomass estimate in a more familiar format.

Using ArcMap™ 9.2 (Environmental Systems Research Institute, Redlands, CA), constraints (exclusions) placed upon this spatial data layer were as follows: (1) Mark Twain National Forest land not being considered for harvest; (2) Ozark National Scenic Riverways; (3) state-owned forest land; (4) forest land managed by the Pioneer Forest; (5) incorporated areas; (6) road rights-of-way; (7) land whose slope exceeds 35 percent, and (8) 3-mile buffer around all major lakes.

Table 1.—Total all-live biomass (million green tons), by diameter class, that would be available in the 44-county area of southern Missouri from fully stocked basal area classes of 80-120 and 120+ ft^2 per acre and accounting for a portion of that biomass being diverted into wood products of higher value than bioenergy

Diameter class (inches)	Total all-live biomass (million green tons) Basal area class					All-live biomass from forest thinning operations (million green tons)			Disposition of all-live biomass from thinning operations	Biomass available for bioenergy (million green tons)
	Total	0-40	41-80	81-120	120+	81-120	120+	Total		
1.0-2.9	13.96	0.56	4.98	6.48	1.93	2.27	0.77	3.04	leave as understory	0.00
3.0-4.9	26.41	0.61	7.22	13.54	5.05	4.74	2.02	6.76	leave as understory	0.00
5.0-6.9	37.70	1.18	12.44	18.47	5.60	6.46	2.24	8.70	100% biomass	8.71
7.0-8.9	50.84	1.32	16.33	25.50	7.69	8.92	3.08	12.00	100% biomass	12.00
9.0-10.9	59.58	1.42	17.47	30.50	10.18	10.68	4.07	14.75	100% biomass	14.75
11.0-12.9	63.75	1.10	17.34	32.24	13.10	11.28	5.25	16.53	40% biomass : 60% grade	6.61
13.0-14.9	57.33	0.91	14.26	29.41	12.75	10.30	5.10	15.40	40% biomass : 60% grade	6.16
15.0-16.9	44.13	0.45	8.64	22.97	12.07	8.04	4.83	12.87	25% biomass : 75% grade	3.22
17.0-18.9	30.68	0.44	5.30	15.76	9.17	5.52	3.67	9.19	25% biomass : 75% grade	2.30
19.0-20.9	23.65	0.56	3.09	11.79	8.21	4.13	3.28	7.41	25% biomass : 75% grade	1.85
21.0-22.9	12.31	0.34	1.31	6.85	3.81	2.40	1.52	3.92	25% biomass : 75% grade	0.98
23.0-24.9	8.01	0.68	1.87	2.85	3.23	1.00	1.29	2.29	25% biomass : 75% grade	0.57
25.0-26.9	3.95	0.07	0.62	1.26	2.00	0.44	0.80	1.24	25% biomass : 75% grade	0.31
27.0-28.9	2.43	0.00	0.38	0.75	1.30	0.26	0.52	0.78	25% biomass : 75% grade	0.20
29.0-30.9	1.70	0.20	0.20	0.57	0.73	0.20	0.29	0.49	25% biomass : 75% grade	0.12
31.0-32.9	9.17	0.00	0.00	0.78	0.14	0.27	0.06	0.33	25% biomass : 75% grade	0.08
33.0-34.9	1.62	0.00	0.00	0.30	1.32	0.12	0.53	0.63	25% biomass : 75% grade	0.16
35.0-36.9	0.64	0.00	0.00	0.28	0.36	0.10	0.14	0.24	25% biomass : 75% grade	0.06
37.0-38.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25% biomass : 75% grade	0.00
39.0-40.9	0.17	0.00	0.00	0.00	0.17	0.00	0.07	0.70	25% biomass : 75% grade	0.02
41.0+	0.48	0.00	0.00	0.00	0.48	0.00	0.19	0.19	25% biomass : 75% grade	0.05
Total	440.27	9.20	111.45	220.31	99.31	77.13	39.72	116.85		58.14

This data layer was then used to create a "moving window" with a 25-mile radius along major highways that would estimate the amount of available woody biomass within that area (Fig. 1). From this analysis we have identified three communities in southern Missouri capable of supporting a sustainable wood-to-energy enterprise: Fredericktown, Cuba, and Thayer. For the purpose of this paper we will limit our discussion to Fredericktown.

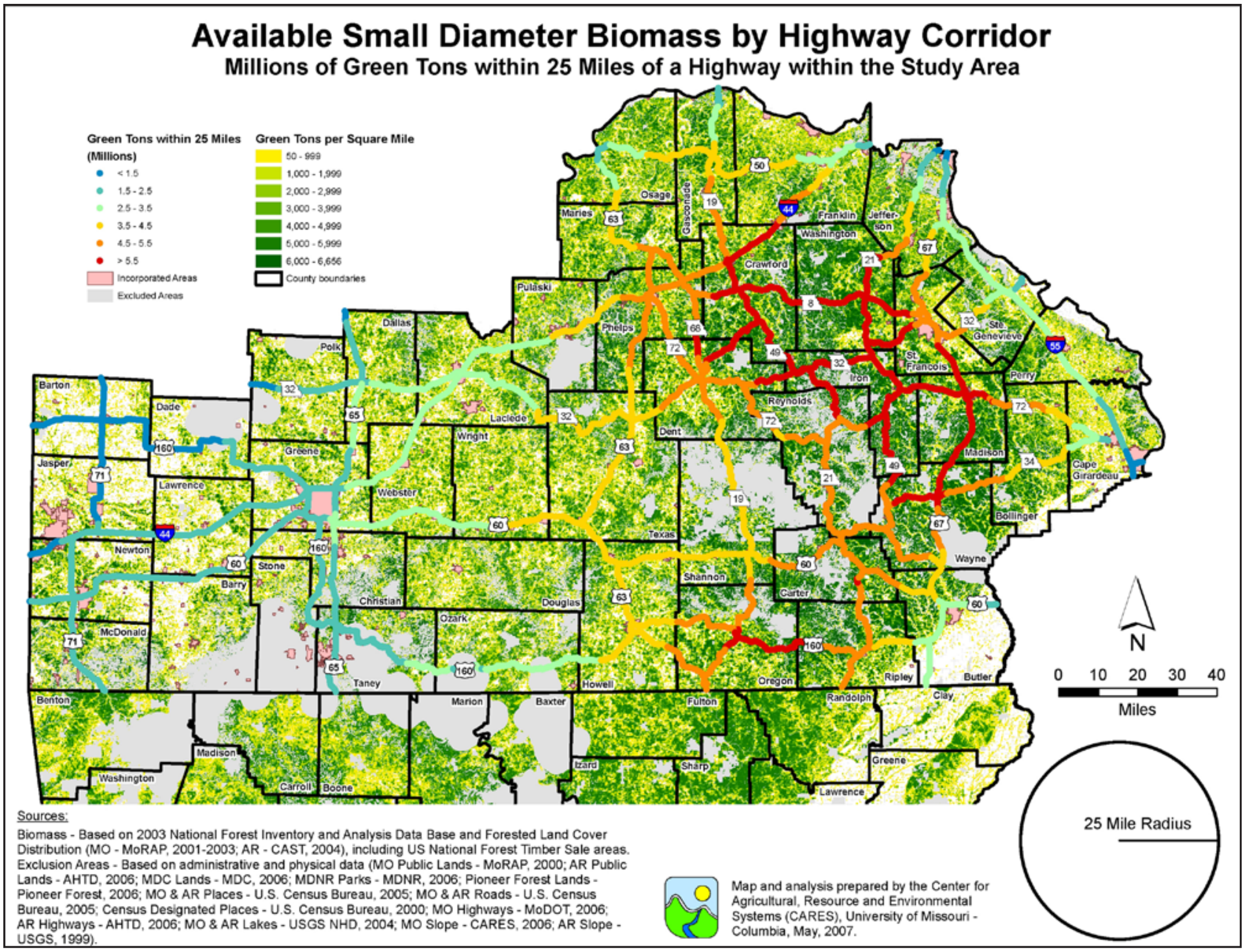

Figure 1.—Spatial distribution of available all-live biomass (green tons) across southern Missouri and within a 25-mile radius of major highway corridors.

PRELIMINARY SUSTAINABILITY ANALYSIS

Table 2 shows the annual forest biomass (green tons) and energy (million BTUs) that would be available for a wood-to-energy facility in Fredericktown, MO, as the radius of the source area expands in 5-mile increments. Available forest biomass was calculated by dividing the forested acres within the source area by 20 (for a 20-year thinning cycle), multiplying by either 0.05 or 0.30 (for the level of landowner participation), and then multiplying by our "typical" biomass yield of 9.5 green tons per acre. To determine the available energy in BTUs we multiplied the green tons per year by 2,000 green lbs per ton and then multiplied that product by 4,300 BTUs per green ton (based upon 50 percent moisture content).

Electrical Energy

Our proposed 25 MW-power plant would require 187,878 green tons annually from slightly less than 20,000 acres. Applying straight arithmetic to a 20-year re-entry interval implies that only one-twentieth of the forested acres for a specified source area radius would be available in a given year. That assumption coupled with a landowner participation level of only 5 percent and 9.5 green tons from forest thinning operations, reveals that even a 50-mile radius would be able to supply only 25 percent of the 187,878 green tons needed.

Table 2.—Annual forest biomass (green tons) and energy (million BTUs) that would be available for a wood-to-energy facility in Fredericktown, MO, as the source area expands based upon a 20-year thinning cycle and landowner participation levels of 5 and 30 percent

Source area radius (miles)	Total acres within source area	Forested acres within source area	Available biomass from forested acres (green tons)		Available energy from forested acres (million BTUs)	
			5% Landowner participation[1]	30% Landowner participation[2]	5% Landowner participation[3]	30% Landowner Participation[3]
5	42,164	23,180	551	3,303	4,735	8,407
10	158,121	97,018	2,304	13,825	19,816	118,896
15	367,632	225,338	5,352	32,111	46,025	276,152
20	649,358	387,393	9,201	55,204	79,125	474,750
25	1,016,054	599,098	14,229	85,371	122,366	734,195
30	1,455,881	805,410	19,128	114,771	164,505	987,030
35	1,916,480	989,830	23,508	141,051	202,173	1,213,037
40	2,305,024	1,148,393	27,274	163,646	234,559	1,407,356
45	2,632,191	1,326,623	31,507	189,044	270,963	1,625,776
50	2,951,908	1,507,945	35,814	214,882	307,998	1,847,987

[1]Available biomass (green tons/yr) = (forested ac/20 yr)*(0.05)*(9.5 green tons/ac)
[2]Available biomass (green tons/yr) = (forested ac/20 yr)*(0.30)*(9.5 green tons/ac)
[3]Available energy (million BTUs/yr) = (green tons/yr)*(2,000 green lb/green ton)*(4,300 BTUs/green lb)

However, if the participation level increased to 30 percent, then all of the plant's energy need could be supplied within a 45-mile radius. The visual impact of these harvesting operations across the landscape would be minimal because only 20,000 acres out of the 1,326,623 forested acres would be thinned in a given year.

Thermal Energy

A thermal plant of similar design to the Northwest University facility would require 29,000 green tons of wood annually from 3,125 acres of forest. With only one out of 20 landowners participating, our proposed sustainable silvicultural prescription would dictate a source area radius of 40 to 45 miles. If the participation level could be increased to one out of 10 landowners, the source area radius would shrink to 15 miles.

While raw material costs can be greatly reduced, the capital cost of plant construction for a facility that produces only low-pressure steam would probably result in a very unfavorable return on the initial investment. The capital cost of building these bioenergy plants will make it critical that every available BTU be converted to its highest and best use first and then capture unused energy in the form of these lower-value energy products, such as low-pressure steam for thermal uses.

Liquid Bio-fuels

A bio-refinery consuming 200,000 green tons annually would require forest thinnings from 21,000 acres. As for the electrical power plant, this facility would have only a fraction (18 percent) of its raw material need met if only 5 percent of the landowners within 50 miles of the plant thinned their forests. However, if the participation level increased to 30 percent then all the plant's wood fiber need could be supplied within a 45-mile radius.

ADDITIONAL CONSIDERATIONS

We realize that one silvicultural prescription will not fit all forested sites in the Missouri Ozarks. Ongoing forest health issues, such as oak decline, and upcoming open woodland restoration efforts on the Mark Twain National Forest will dictate prescriptions more aggressive than simple forest thinning. As a result, more than the 9.5 green tons from our "typical" acre will be available, potentially allowing smaller source areas for a wood-to-energy facility.

The area required to sustain a bioenergy plant could also be reduced by taking into account fiber from mixed stands of oak and pine, or even pure stands of pine. These cover types were intentionally omitted from this analysis in an attempt to provide as uniform a feedstock as possible given (1) the mosaic of the state's forests and (2) the fact that boilers and the current technology of bio-refineries tend to like uniform raw material in order to maximize product yield and minimize maintenance and repair costs.

Any financial analysis for a bioenergy plant will have to consider the cost of harvesting and transporting the wood to the power/thermal plant or bio-refinery. This is where the real challenge lies. For forest thinning operations to be economical, the number of times the tree/log/residue is handled must be minimized. For the operation to be sustainable, there must be minimal damage to the trees left standing and other best management practices followed. In addition, increasing fuel costs will put pressure on the distance that chips or round wood can be economically delivered from the forest to the bioenergy plant. These added costs will either limit the size of wood-to-energy enterprises, encourage mobile bio-refineries, or result in more aggressive harvesting. The last outcome has the potential of raising heated debate similar to the chip mill controversy of the late 1990s; another option for removing low-grade material from Missouri's forests may be eliminated.

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EFFECTIVENESS OF THE FOREST STEWARDSHIP PROGRAM IN CONSERVING NATURAL RESOURCES ON PRIVATE LANDS IN INDIANA

Andriy V. Zhalnin, Shorna R. Broussard, and Richard L. Farnsworth[1]

Abstract.—Forest ecosystems are a dominant component of the nation's landscape but are a challenge to manage because of diverse ownership and policy objectives. Privately owned, nonindustrial lands comprise nearly half of all forests in the United States (42 percent); nearly 10.3 million citizens own 393 million acres. A number of landowner assistance programs are designed to help conserve natural resources on private lands in the United States. However, little research has been done that evaluates the impact of these programs on the conservation of natural resources on private lands. In this study we focused on the Forest Stewardship Program, which is termed the Classified Forest Program (CFP) in Indiana. Through a spatial analysis, we assessed: (1) the effectiveness of the CFP in addressing high-priority lands; (2) how the distribution of high-priority land varies by land enrolled in the CFP and private forest lands not enrolled in the program; and (3) the effectiveness of the CFP in conserving threatened and endangered wildlife habitat, riparian corridors, and contiguous patches of forest land. We found significant differences between conserved resources on private lands enrolled in the CFP, and private lands outside the program, which shows the significant impact of the Forest Stewardship Program on conserving natural resources in Indiana.

INTRODUCTION

With 42 percent of the forest land (393 million acres) in the contiguous United States owned by 10.3 million family forest owners, (Butler and others 2004), these owners have a tremendous impact on the environmental and biological quality of forest land in the United States. In Indiana, private forest owners are the dominant ownership regime with only 14.9 percent of the entire state area is in public ownership (federal and state). According to latest statewide available data, 20.4 percent of the land in Indiana is forested (MRLC Consortium 2001), of which private forest lands comprise 75.1 percent. Private forest land management is impacted by the fragmentation of parcels, ownerships, and forests (Sampson and DeCoster 2000). Increasingly greater numbers of forest landowners, who in turn own smaller parcels, exacerbate the difficulty of retaining the cohesive landscapes necessary for sustaining biological diversity and ecosystem health (Plantinga and others 2007). The government uses many policy instruments to address the issue of conserving forest lands in the United States. However, little research has been done that evaluates the impact of landowner assistance programs on the conservation of natural resources on private lands.

OBJECTIVES

In this study we looked at the Forest Stewardship Program in Indiana, where it is called the Classified Forest Program. We assessed the following: (1) the effectiveness of the CFP in addressing high priority lands; (2) how the distribution of high-priority land varies by land enrolled in the CFP versus private forest lands not enrolled in the program; and (3) the effectiveness of the CFP in conserving threatened and endangered wildlife habitat, riparian corridors, and contiguous patches of forest land.

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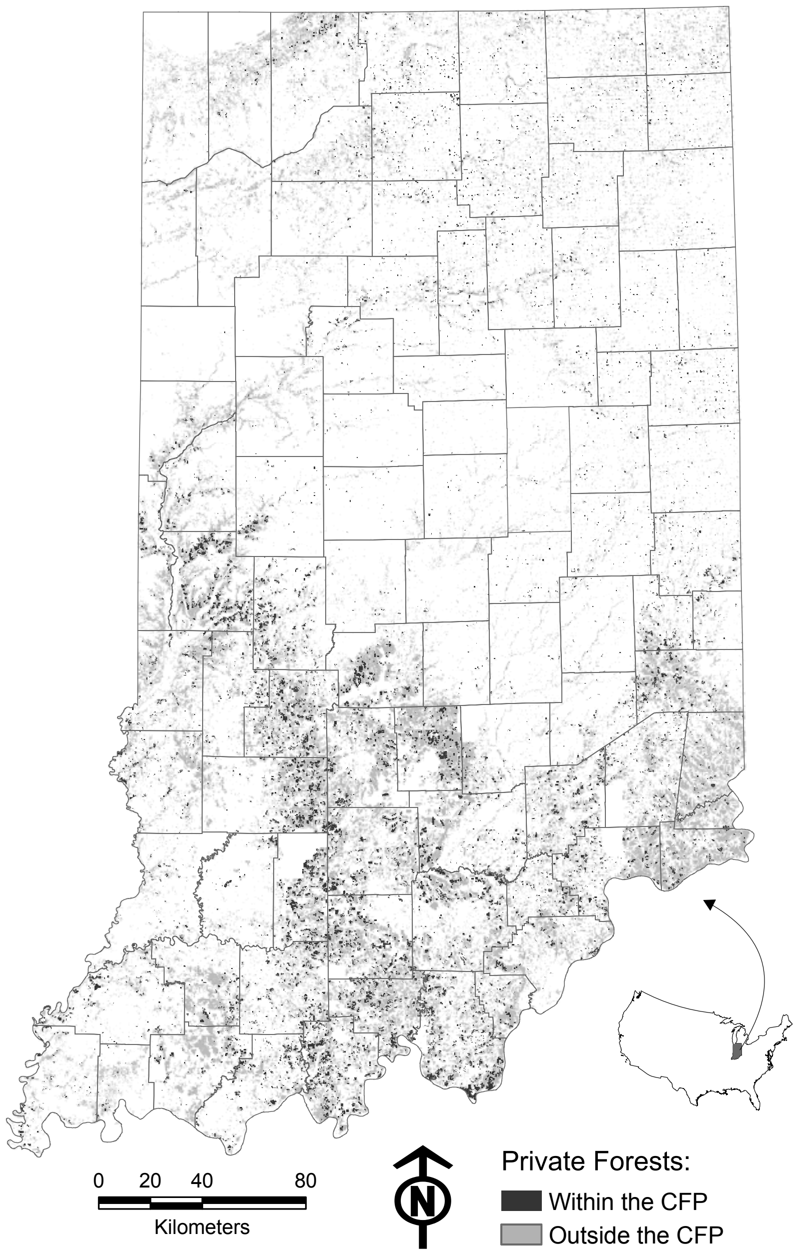

Figure 1.—Privately owned forests in Indiana within the Classified Forest Program (CFP) and outside the CFP.

METHODS

Our study encompassed all privately owned forest land in the state of Indiana (Fig. 1). All publicly owned lands were masked out of the analysis. This study used data that originated from two projects. Private forests were digitized within the Forest Stewardship Program Classified Forest (CFP) database project. The Spatial Analysis Projects (SAP, described fully in later section) provided us with an aggregated layer of Forest Stewardship potential for the evaluation of natural resources within private forests.

Forest Stewardship Plans Geodatabase

Indiana's CFP is specifically designed to help keep Indiana's private forests intact. Eligibility for this voluntary landowner incentive program is based on land tracts being a continuous forested area of 4 hectares or more that support a growth of native or planted trees and that have been set aside for the production of timber and wildlife, the protection of watersheds, or the control of soil erosion (Indiana Dept. of Nat. Res. 2007). Both native timber land and land planted to an acceptable species of trees are eligible for classification. Eligible woodlands may be either native forests containing at least 9.2 m^2 of basal area per hectare or at least 2,470 timber-producing trees (any size) per hectare. Tree plantations with at least 300 well established timber-producing trees are also eligible to be a Classified Forest. Certain activities cannot take place on Classified Forest lands: grazing by domestic livestock; building of houses, sheds, etc.; intentional burning unless prescribed under a written management plan; and growing Christmas trees. In return for meeting program guidelines, landowners receive property tax breaks, forestry literature, and periodic free inspections by a professional forester while the forest is enrolled in the program.

Copies of legal descriptions, surveys, and maps of the Classified Forest properties enrolled in the program in 2005 were collected from Division of Forestry, Indiana Department of Natural Resources (IDNR) offices, scanned, and then entered into a Geographic Information Systems (GIS) database using UCLID's IcoMap (4.0 Extracts Systems, LLC, Madison, WI 2006), an add-on program for ESRI's ArcGIS 9.1 (Environmental Systems Research Institute, Redlands, CA 2006). At the time of the data entry a color 1-m resolution set of aerial photographs from the summer 2005 (Indiana Geograph. Infor. Counc. 2005) was loaded to serve as a secondary check to ensure that parcels were being digitized in their correct location. All digitized polygons representing Classified Forest properties within the study area were linked to a landowner Microsoft Access database supplied by the IDNR Division of Forestry. The following database attributes were joined to the GIS layer: name of the owner, surveyed area, and type of enrollment (new property, addition, changed ownership, withdrawal). Each parcel was assigned a unique ID number. We defined a parcel as the total forest area enrolled in one plan for a given landowner. Parcels having multiple polygons of forest were referred to as having tracts, and are lettered A, B, C, etc. within a given parcel ID.

Spatial Analysis Project Layers

In 2004, the U.S. Forest Service initiated the Spatial Analysis Project, a pilot program to develop and test a consistent methodology to locate stewardship parcels, to assess the impact of the Forest Stewardship Program across the landscape, and to use the collected data analyses to make further improvements, if necessary, in the Forest Stewardship Program (U.S. Forest Service 2007a). Four states participated in the pilot program (Connecticut, Maryland, Massachusetts and Missouri). After the pilot phase of the SAP, Purdue University and the IDNR received funding in 2004 to digitize stewardship parcels and apply the SAP methodology (U.S. Forest Service 2007b). The purpose of the Spatial Analysis Project is to create an aggregated data layer for a state that represents levels of potential benefit from -- or suitability for inclusion in -- the Forest Stewardship Program as delivered by state forestry agencies and the U.S. Forest Service. The goal of the SAP was to spatially assess and analyze the status and distribution of existing Forest Stewardship plans and their proximity to important forest lands, thus enabling forest managers to better capture and articulate Forest Stewardship Program impact to date.

Private land program and GIS staff from the four states involved in the pilot SAP effort, along with Forest Service program and GIS staff, identified 12 factors which help quantify the "Stewardship potential" of a given piece of land and which were available as GIS data layers. The factors were differentiated into two groups: resource potential and resource threats. The resource potential factors are as follows: riparian zones, priority watersheds, forest patch size, natural heritage data, public drinking water supply sources, private forest lands, proximity to public lands, wetlands, and topographic slope. The resource threat factors

Table 1.—Weighting of 12 data layers for the Spatial Analysis Project in Indiana

Data layer	Number of votes	Weighting (%)	Weighting applied
Fire risk	6	0.78	0.007
Impaired watersheds	44	5.74	0.057
Slope	48	6.27	0.062
Natural Heritage Data	50	6.53	0.065
Wetlands	52	6.79	0.067
Public water supply	55	7.18	0.071
Proximity to public lands	56	7.31	0.073
Forest health (pests)	67	8.75	0.087
Risk of development	69	9.01	0.090
Unfragmented forest (>20 ha)	96	12.53	0.125
Riparian corridors	98	12.79	0.128
Private forests	125	16.32	0.163
Total	766	100.00	1.000

consisted of forest health, development level, and wildfire assessment. Certain lands such as water bodies, completely urbanized areas, and public lands were not eligible for inclusion in the Forest Stewardship Program and were excluded from analysis.

In assessing the resource threat of development, we adopted an approach developed by the North Central Research Station, Forest Inventory and Analysis Program. This approach uses housing density as a proxy for identifying areas of economically viable timber production. This group's analysis includes a national map of housing density for 2000 and estimated housing density for 2030, thus giving us a glimpse of where urbanization will compete for agricultural and forested lands (Stein and others 2005). Using data from Stein and others (2005), we coded housing density for 2000 and 2030 into one of three possible categories: 0 to 16 housing units per square mile, 17 to 64 housing units per square mile, and more than 64 housing units per square mile. Commercial tree production is most viable in cells with a housing density of 0 to 16 housing units per square mile. These areas are the least threatened and therefore of lower immediate priority than lands transitioning to the moderate housing density. Nonetheless, these low-density areas should be considered appropriate and priority targets for stewardship. Commercial tree production and harvesting is problematic when housing density is 16 to 64 units per square mile. Housing densities above 64 units per square mile reflect highly urbanized areas. Remaining patches of trees are too small and the logistics of harvesting make commercial timber activities generally infeasible.

Once the 12 common factors were identified, each state examined these 12 factors and determined the relative importance of each based on state-specific conditions. The Indiana Forest Stewardship Committee and employees of the IDNR Division of Forestry Cooperative Forest Management Section each went through a focus group session by which they prioritized the above 12 factors. Each participant was allocated a total of 25 votes with a maximum of five votes per data layer; participants could choose not to allocate votes to a data layer. The weightings for each of the 12 factors were then averaged across the two rounds of voting to yield our final weighting scheme (Table 1).

The 12 factors were then combined in a GIS overlay analysis which took into account the weight for each factor. The final product was a single data layer which represents the suitability of the land for inclusion in the Forest Stewardship Program. Values from this analysis range from 0 to 1, with a value of 1 representing the highest level of suitability. To make interpretation of results easier and to allow for computation of area statistics, the continuous cell values were categorized into three classes based on natural break classification (Jenks 1963): (1) low: 0-0.093; (2) medium: 0.094-0.308; and (3) high: 0.309-1.000.

To assess the effectiveness of the Forest Stewardship Program, we overlaid parcel polygons on the stewardship potential layer that identifies low, medium, and highly suitable lands and tested the following hypotheses:

1. The CFP is successful in conserving forest resources with high forest stewardship potential.
2. A significantly greater proportion of CFP lands is of high forest stewardship potential compared to private forest lands not enrolled in the program and public lands.

For hypotheses (1) and (2) Chi-square test was used to determine whether: (1) three categories are significantly different for the lands within CFP; (2) the area distribution among three categories within the land enrolled in the CFP is significantly different from the area distribution among three categories outside the CFP.

To evaluate effectiveness in conserving valuable natural resources, we overlaid CFP parcel polygons on the GIS data layers that are of high conservation priority: riparian corridor buffers, contiguous forest patches, and habitats of threatened and endangered species. Each layer is represented by raster layer with 30-m pixel size. The riparian corridor buffers layer has a 100-m buffer around perennial streams and river features. The original vector data was obtained at a scale of 1:100,000 from U.S. Geological Survey (USGS) (U.S. Geol. Survey 2001,) buffered at 100-m distance from streams, and converted into 30-m grid cells. The threatened and endangered forest species habitat layer was created from mapped data on forest-dwelling endangered species sightings (plants and animals) in Indiana (provided by IDNR) buffered by 0.8 km. The contiguous forest patch layer includes forested areas greater than or equal to 20 ha of forest. The raster database of forest originated from National Land Cover Dataset of 1992 and was obtained from USGS (MRLC Consortium 2001). Forests were removed within 30-m buffer areas around federal and state roads to account for fragmentation of forest cover caused by roads, and forest patches at least 50 acres in size were identified. Lastly, we calculated area statistics for each resource for the areas within CFP and tested the following hypotheses:

1. The CFP is successful in conserving forests within riparian corridors as compared to non-CFP lands.
2. The CFP is successful in conserving forests with threatened and endangered species habitat as compared to non-CFP lands.
3. The CFP is successful in conserving contiguous patches of forest land as compared to non-CFP lands.

RESULTS

As of 2005, 9,440 parcels (12,180 tracts) that were owned by 7,420 unique owners were enrolled in CFP in Indiana. The average size of parcel was 26.48 ha with a standard deviation of 38.7 ha and standard error of 0.35 ha. The smallest parcel was 0.97 ha and the largest was 603 ha. The total area of parcels enrolled in CFP and digitized was 197,345 ha, which is 2.1 percent of the entire state and 10.3 percent of the total forested land in Indiana. Our first task was to determine if there is a difference in SAP identified categories

Table 2.—Proportion of three Forest Stewardship potential categories within the private lands enrolled in Classified Forest Program (CFP) in Indiana

Forest Stewardship potential category	Hectares	%
	Private lands, enrolled in CFP program	
Low	18,535	9.4
Medium	49,354	25.0
High	129,281	65.6
Total	197,345	100.0
Chi-square statistics	χ^2 =50.43; χ^2.0001 = 18.42; df=2; p<0.0001	

Table 3.—Distribution of three Forest Stewardship potential categories within the private forest area enrolled in the Classified Forest Program (CFP), outside the program, and within the entire state of Indiana

Forest Stewardship potential category	Private forests enrolled in CFP, ha (%)	Private forests not enrolled in CFP, ha (%)	Private forests of the entire state, ha (%)
	------------Hectares------------		
Low	136 (0.1)	5,409 (0.4)	5,745 (0.3)
Medium	37,156 (22.6)	536,428 (36.7)	622,953 (32.6)
High	126,909 (77.3)	920,552 (62.9)	1,282,562 (67.1)
Total	164,201 (100.0)	1,462,389 (100.0)	1,911,260 (100.0)
	Chi-square statistics		
Chi-square statistics for private forests enrolled in CF and not enrolled in CF	χ^2 =8.87; χ^2.05 = 5.99; df=2; p<0.05		

of valuable lands within CFP-enrolled properties. The distribution of area was the following: 65.6 percent of CFP enrolled lands were in the highly suitable category, 25.0 percent were in the medium category and 9.4 percent were in low suitability category (Table 2). The χ^2 test showed a significant (p<0.0001, df=2) difference of existing distribution from the hypothesized (when nontargeted by the program) distribution of SAP categories. This finding supports our hypothesis that CFP is effectively targeting lands that are estimated as highly valuable by the SAP project.

Results of the comparison between private forest lands within the CFP to private forest lands not enrolled in the program, and to private forest lands of the entire state, show that enrolled areas have a higher proportion of valuable lands (77.3 versus 62.9 and 67.1 percent respectively, Table 3). The conducted χ^2 square test (p<0.05, df=2) rejected the null hypothesis that distribution of categories among the above-named areas is equal and supports an alternative hypothesis of the selective nature of CFP (Table 3).

CFP-enrolled lands have 10.2 percent of their area located within riparian corridors (Table 4). Private lands outside the program have 14.2 percent of their forested area within riparian corridors, which is similar to the entire state (13.4 percent). The proportion of contiguous forested area shows that 92.9 percent of the CFP-enrolled lands are located within unfragmented forests, while the proportion on private lands outside the CFP is much lower (69.8 percent, table 4). The proportion of threatened and endangered species of forest habitats area within the CFP is 14.3 percent while the proportion for the lands outside the CFP is somewhat lower (9.7 percent, Table 4).

Table 4.—Proportions of selected natural resources within forest areas of different ownership status in Indiana

Enrollment status of private forests	Total area of resource, ha (%)	Total forested area, ha (%)	Proportion from the entire state private forests, %
		Forested riparian corridor area	
Enrolled in CFP	16,701 (10.2)	164,201 (100)	41.7
Not enrolled in CFP	207,737 (14.2)	1,462,389 (100)	58.3
Entire state	255,839 (13.4)	1,911,260 (100)	100.0
		Contiguous forest (>20 ha)	
Enrolled in CFP	152,565 (92.9)	164,201 (100)	57.1
Not enrolled in CFP	1,021,347 (69.8)	1,462,389 (100)	42.9
Entire state	1,449,015 (75.8)	1,911,260 (100)	100.0
		Threatened and endangered species of forest habitats	
Enrolled in CFP	23,429 (14.3)	164,201 (100)	59.5
Not enrolled in CFP	142,026 (9.7)	1,462,389 (100)	40.5
Entire state	272,935 (14.3)	1,911,260 (100)	100.0

DISCUSSION

One of the shortcomings pointed out by researchers when studying conservation programs is a lack of biological monitoring, namely quantitative monitoring of biological targets, which hampers assessment of conservation programs' effectiveness (Kiesecker and others 2007). At the same time, geospatial technology including remote sensing and GIS is a readily available tool for monitoring and assessment of conservation program conditions (Williams and others 2006). In our study we used available GIS data to determine if the CFP in Indiana addresses areas that are defined by SAP research as highly suitable for natural resources conservation. We found that although prior to 2005 the CFP in Indiana did not target areas specifically selected because of high biological value, 65.6 percent of lands enrolled in the program were of high conservation quality. According to Chi-square analysis of the distribution of stewardship potential categories within CFP, lands within CFP show a difference from random distribution of such categories. In a similar analysis of upland-nesting duck species in North and South Dakota, Reynolds and others (2006) found that 75 percent of Conservation Reserve Program contracts were in medium to high duck population category (19-10 pairs/km^2) and 25 percent in areas of low populations (less than 10 pairs/km^2). Comparison of proportions on lands within CFP to proportions outside the program shows significant difference in stewardship potential categories. However, while encompassing a larger proportion of highly suitable lands within the CFP (77.3 percent), the area proportion is not dramatically larger than that outside the program (62.9 percent) or the entire state (67.1 percent), apparently due to the nonselective nature of the program.

The question arises as to what might be defined as effective conservation. Merriam-Webster's Collegiate Thesaurus defines "effectiveness" as the power to produce a desired result (Merriam-Webster 2003). The objectives of the Indiana Classified Forest and Wildlands Act are "to encourage better woodland and wildlife stewardship, and protection of Indiana watersheds"(IDNR 2007). Although this legislation has specific requirements for lands that may be enrolled in the program, it defines only vaguely what resources should be conserved and does not quantify how much of those resources should be retained in order to provide a better stewardship.

In a similar assessment of grassland habitats within the Operation Burrowing Owl program in Canada, authors found burrowing owls on 66 percent of conserved sites, as opposed to 49 percent of random sites. They concluded that the program was effective in conserving habitats (Warnock and Skeel 2004). Our analysis of high-priority lands shows that the difference between proportions of contiguous forest within enrolled and nonenrolled private forests is 23.1 percent. The difference in proportions of riparian corridors is -4.0 percent (minus sign denotes that a smaller percentage was conserved on CFP-enrolled land), and habitats of threatened and endangered species (TES) 4.6 percent. We conclude that the most successfully conserved resource is contiguous forest, followed by TES habitats and riparian corridors.

Our study implies that the Forest Stewardship Program in Indiana has great potential for conserving natural resources on private forest lands of the state. We found that GIS analysis can considerably enhance implementation of landowner assistance programs. If a conservation program aims at natural resources on a broader scale, it is highly desirable to take a comprehensive approach when lands are assessed for enrollment into such a program due to intricate, and not always well understood, relationships among ecosystem components. The latter may include wildlife and plant habitats, water resources, threats to natural resources from pests or development, and so on. This list may differ depending on the region of interest. Better results can be achieved by targeting areas of high conservational priority. For example, owners can be encouraged by means of higher incentives for enrolling parcels located on the land that are highly suitable for forest stewardship. Incentives such as this example might be worth considering to improve protection of Indiana's riparian lands.

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FOREST BIOMETRICS AND MODELING

A WHOLE STAND BASAL AREA PROJECTION MODEL FOR APPALACHIAN HARDWOODS

John R. Brooks, Lichun Jiang, Matthew Perkowski, and Benktesh Sharma[1]

Abstract.—Two whole-stand basal area projection models were developed for Appalachian hardwood stands. The proposed equations are an algebraic difference projection form based on existing basal area and the change in age, trees per acre, and/or dominant height. Average equation error was less than 10 square feet per acre and residuals exhibited no irregular trends.

INTRODUCTION

The ability to estimate future yields of Appalachian hardwoods has been and still is of great interest to forest practitioners in this region. Recently, whole-stand cubic volume and board foot volume prediction equations were developed for this area based on stand basal area per acre and average dominant height (Brooks and Wiant 2004, 2005). Volume predictions within 10 percent of actual yields were realized with this system. The cubic yield model can predict current conditions based on measurements of stand basal area and the average dominant height of all trees, regardless of species. To expand the usefulness of this model to a yield projection system, dominant height and basal area projection models are necessary. For future estimates of average dominant height, existing site index models can be employed using curves for the main species in the stand (Carmean and others 1989). For future basal area estimates, a projection model based on existing basal area and commonly measured stand variables is needed. This study evaluates several model formulations to develop such a projection equation.

METHODS

Three data sources were used in this investigation, the yield tables developed for Appalachian hardwoods by Schnur (1937) and two sets of remeasurement data from permanent plots from north central West Virginia. From the Schnur yield tables, basal area per acre, trees per acre, and average oak dominant height were obtained for ages 10 to 100 covering site index values of 40 through 80. The permanent plot data were obtained from the West Virginia University Research Forest located in Monongalia and Preston counties, WV. These data include four 0.5-acre control plots established in the late 1940s and early 1950s and remeasured at approximately 5-year intervals through the early 1990s. The second dataset is based on 40 permanent 0.2-acre continuous forest inventory plots established in 1999 and having at least two remeasurements. The permanent plot data reflect even-aged stands with no history of cutting. Stand age ranged from 17 to 74 years of age. A description of stand parameters is displayed in Table 1.

The permanent sample plots consist of two broad cover types (mesophytic and oak types). The former includes the yellow-poplar-white oak-northern red oak (SAF type 59) and the yellow-poplar type (type 57) (Eyre 1980). The oak type is best described as the white oak/black oak/northern red oak (type 52) and the chestnut oak type (type 44). Although three distinct datasets were combined for this analysis, values for all

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Table 1.—Descriptive statistics for the stand-level growth and yield data used in the basal area projection models

Variable	N	Mean	Std Dev	Min	Max
Age1 (yr)	147	56.9	19.9	10	90
Age2 (yr)	147	62.4	18.8	20	100
TPA1	147	545.3	880.3	95.0	6850.0
TPA2	147	389.8	413.3	95.0	3260.0
DHT1 (ft)	147	71.6	22.1	8.0	107.6
DHT2 (ft)	147	75.9	20.5	17.0	124.7
BA1 (ft^2)	147	127.6	37.8	36.0	213.1
BA2 (ft^2)	147	135.5	34.9	60.0	218.9

Age_i = Current (i = 1) or projected stand age (i = 2)
TPA_i = Current (i = 1) or projected (i = 2) trees per acre
DHT_i = Current (i = 1) or projected (i = 2) stand dominant height
BA_i = Current (i = 1) or projected (i = 2) stand basal area per acre

stand variables overlap with respect to age, trees per acre, basal area per acre, and stand dominant height. The data from the Schnur yield tables for site index 40 provided the lowest range of data while some of the 40 permanent plots extended the upper range of the data. Inclusion of such a wide range of overlapping stand variables was deemed beneficial when attempting to develop a single model form for predicting future values for oak dominated hardwood stands over a wide distribution of current stand conditions.

After some initial evaluation, two prospective model forms were selected for testing. The first is based on an algebraic difference equation developed by Pienaar and Shiver (1986) involving current and future estimates of stand trees per acre (TPA) and stand average dominant height:

$$BA_2 = Exp\left[Ln(BA_1) + \beta_1\left(Ln(DHT_2) - Ln(DHT_1)\right) + \beta_2\left(Ln(TPA_2) - Ln(TPA_1)\right)\right] \qquad [1]$$

where BA_i is stand basal area per acre (ft^2) at time period i (1 = current, 2 = projected), DHT_i is the average stand dominant height at time period i, TPA_i is stand trees per acre at time period i, Ln is the natural logarithm, and βi are the parameters estimated with the data (i = 1…2).

This model form has an advantage in that stand age is not explicitly required, although some estimate of future stand density (TPA_2) is needed. The second equation is a modified form of an equation developed by Pienaar and others (1988) that involves the initial basal area and the change in stand average dominant height, trees per acre, and stand age:

$$BA_2 = Exp\left[\begin{array}{l} Ln(BA_1) + \beta_1\left(\frac{1}{A_2} - \frac{1}{A_1}\right) + \beta_2\left(Ln(DHT_2) - Ln(DHT_1)\right) + \\ \beta_3\left(Ln(TPA_2) - Ln(TPA_1)\right) + \beta_4\left(\left(\frac{Ln(DHT_2)}{A_2}\right) - \left(\frac{Ln(DHT_1)}{A_1}\right)\right) + \\ \beta_5\left(\left(\frac{Ln(TPA_2)}{A_2}\right) - \left(\frac{Ln(TPA_1)}{A_1}\right)\right) \end{array}\right] \quad [2]$$

where A_i is the stand age at time period i (1 = current, 2 = projected) and all other variables and parameters are as previously defined.

Both equation forms have been commonly applied to southern pine growth and yield systems, but no record has been found of their application in Appalachian hardwoods.

The full form of each of the projection models was fit to the hardwood growth data utilizing all non-overlapping growth intervals. Models were fit using SAS Proc NLIN (SAS 2002). Evaluation of model goodness of fit was based on residual analysis, model root mean squared error (RMSE), and average bias (BIAS) as defined as:

$$BIAS = \frac{\sum_{i=1}^{n} \hat{BA} - BA_i}{n} \quad [3]$$

RESULTS

Equation 1 and 2 were fit to the hardwood growth and yield data. Non-significant parameters were removed from the full equation form and refit to the original dataset. The model and all parameter estimates in equation 1 were significant ($p < 0.0001$), and so the final model form is the same as the full model:

$$BA_2 = Exp\left[Ln(BA_1) + 0.4879*\left(Ln(DHT_2) - Ln(DHT_1)\right) - 0.1462*\left(Ln(TPA_2) - Ln(TPA_1)\right)\right] \quad [4]$$

For equation 2, β_1, β_2, and β_3 were not significant and were sequentially removed from the equation. Final equation parameter estimates and fit statistics are displayed in Table 2. This equation is of the form:

$$BA_2 = Exp\left[\begin{array}{l} Ln(BA_1) + 0.2139*\left(Ln(DHT_2) - Ln(DHT_1)\right) - \\ 3.5966*\left(\left(\frac{Ln(DHT_2)}{A_2}\right) - \left(\frac{Ln(DHT_1)}{A_1}\right)\right) \end{array}\right] \quad [5]$$

EXAMPLE

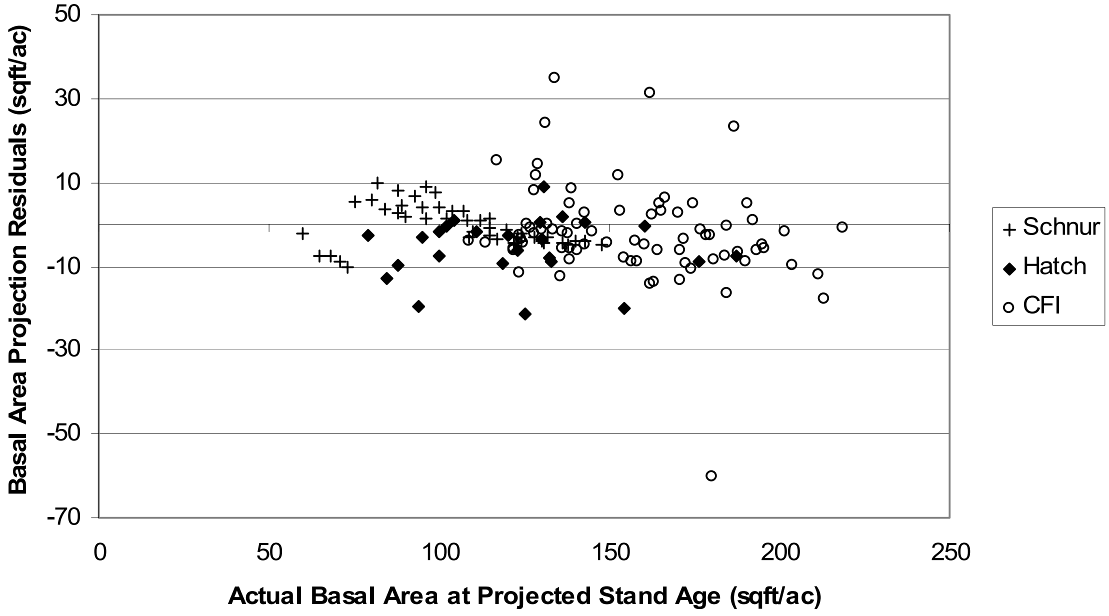
Table 2.—Parameter estimates and fit statistics for the stand-level hardwood basal area projection models.

Equation	Parameter	Estimate	RMSE (ft^2/ac)	BIAS (ft^2/ac)
1	β1	0.488	9.786	-2.181
1	β2	-0.146		
2	β2	0.214	8.131	-2.203
2	β4	-3.597		

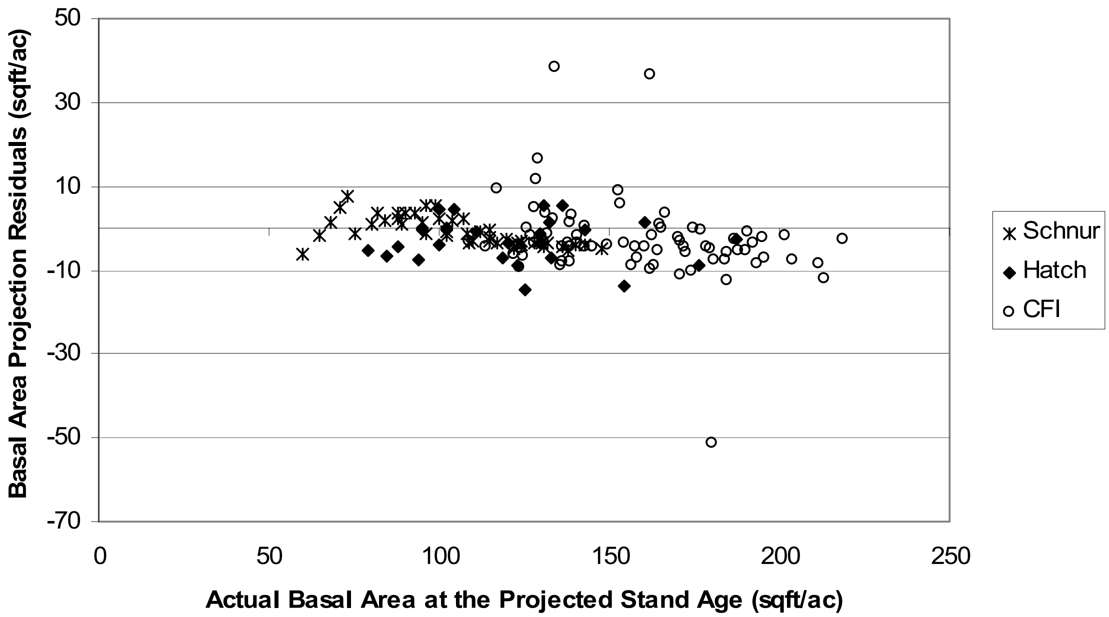
Residual analysis across all model variables did not indicate any irregular model behavior for either equation. Residuals by projected basal area for both equations and by data source are shown in Figure 1. Equation 1 had an average BIAS of -2.181 square feet per acre and a RMSE of 9.786 square feet per acre. Equation 2 had an average BIAS of -2.203 square feet per acre and a RMSE of 8.131 square feet per acre. For equation 2, the largest residuals were associated with three of the 77 growth intervals for the 40 permanent sample plots, but, 95 percent of the basal area residuals were within +/- 15 square feet per acre, indicating good prediction capability. Since these three plots represent actual stand values, they are not considered outliers and were included in the model fitting process. For equation 2, none of the basal area residuals from the Schnur yield tables were greater than +/- 10 square feet per acre which is likely due in part to the fact that these data represent average yield curve points thus minimizing natural plot-to-plot variation. Over all datasets, 94 percent of the basal area residuals for equation 2 were less than +/- 11 square feet per acre (Fig. 1).

CONCLUSIONS

A whole stand basal area projection model was developed for unthinned hardwood stands in the central Appalachian region. Since Schnur's (1937) data were based on predominately oak-dominated stands, these models are recommended for oak-dominated mixed Appalachian hardwood forests. Two model forms are presented, each with some limitations in application. Equation 1 is based on existing basal area per acre and an estimate of change in average dominant height and trees per acre. Current basal area per acre can be obtained through typical inventory procedures, while projected dominant height can be estimated using currently published site index/dominant height equations. Projected survival may be more difficult to estimate based on the lack of stand-level survival models for this region. Additional research is underway to rectify this limitation. Equation 2, having the smaller RMSE, requires estimates of existing basal area per acre as well as current and projected dominant height. These values, too, can be estimated based on current inventory data and existing site index/dominant height functions. This model form also requires current and projected stand age. In hardwood regions forest managers historically have been reluctant to estimate stand age during typical inventory procedures. However, since these models are based on even-aged stands, current stand age should be easily acquired through harvesting records. Thus equation 2 may be the easiest avenue for estimating future basal area and hence future cubic foot volume yields utilizing the whole-stand cubic volume equations by Brooks and Wiant (2004).



(a)



(b)

Figure 1.—Basal area projection residuals $\left(\hat{BA} - BA_i\right)$ for equation 1 (a) and equation 2 (b).

EXAMPLE

Inventory data for one of the long-term remeasurement plots at age 34 (A1) show 438 TPA, 102.24 square feet of basal area per acre, and an average dominant height of 54.7 feet. Current yield using equations by Brooks and Wiant (2004) would be:

$$CFAC = 0.40243*(102.24*54.7)$$

$$CFAC = 2,250.6\ \frac{ft^3}{ac}$$

Actual cubic foot volume for this stand is 2,355.1 cubic feet per acre.
If the estimated dominant height at age 58 is 72.4 feet, projected basal area for this stand at age 58 (A2) is:

$$BA = Exp\left[Ln(102.24) + 0.2139*\left(Ln(72.4) - Ln(54.7)\right) - 3.5966*\left(\left(\frac{Ln(72.4)}{58}\right) - \left(\frac{Ln(54.7)}{34}\right)\right)\right]$$

$$BA = 127.11\ \frac{ft^2}{ac}$$

Actual basal area per acre for this stand is 130.8 square feet per acre. Our estimated cubic foot volume at age 58 is:

$$CFAC = 0.40243*(127.12*72.4)$$

$$CFAC = 3,703.5\ \frac{ft^3}{ac}$$

Actual volume for this stand is 4,096.4 cubic feet per acre, an error of slightly less than 10 percent.

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ADAPTATION OF THE QBR INDEX FOR USE IN RIPARIAN FORESTS OF CENTRAL OHIO

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Abstract.—Although high quality riparian forests are an endangered ecosystem type throughout the world, there has been no ecological index to measure the habitat quality of riparian forests in Ohio. The QBR (qualitat del bosc de ribera, or riparian forest quality) index was developed to assess the quality of habitat in Mediterranean forested riparian areas, and we have modified this index for use in central Ohio. Only a few changes were made to the original QBR index to adapt it for use in central Ohio. The changes resulted in scores that reflected the habitat quality of riparian forests along central Ohio streams more accurately than the original index would have. Sixty study sites were chosen for testing this index in three study watersheds (Big Darby Creek, Little Darby Creek, and Walnut Creek) and all sites were placed into habitat quality categories based on their scores. The QBR index appears to be useable to assess riparian forest habitats in central Ohio, and can be used to assess the progress of restoration projects, determine high quality riparian areas for conservation, and assess the quality of habitat for entire watersheds or study areas.

INTRODUCTION

A riparian area is defined as the transitional zone between a river or stream and the adjoining terrestrial upland ecosystem, including both the stream channel itself and the surrounding land that is influenced by fluctuating water levels (Corbacho and others 2003, Goebel and others 2003). These forested areas support high biodiversity, provide water quality protection, naturally control floods, stabilize stream banks, provide wildlife habitat, and allow for direct human benefits such as recreation and aesthetics (Carver and others 2004, Greenwald and Brubaker 2001, Opperman and Merenlender 2000, Tockner and Stanford 2002). Although all of the services provided by these ecosystems are critical ecological functions, riparian forests are among the most threatened ecosystem types in the world (Tockner and Stanford 2002, Alpert and others 1999).

Degradation of riparian forests occurs for many reasons. Riparian areas are subjected to several natural disturbance types, such as flooding, fire, wind, insects, and diseases. Humans have introduced disturbances into this ecosystem type and have also altered the natural disturbance regimes (Miller and others 2006, Yates and others 2004). The building of dams, channelization of streams, agricultural conversion, and urban development destroy natural vegetation and floodplains, and alter flooding cycles for the riparian area (Bunn and others 1999, Friedman and Scott 1995, Raven and others 1998, Salinas and others 2000).

The QBR index ("qualitat del bosc de ribera" or riparian forest quality) is an easy-to-use field method for assessing the habitat quality of riparian forests. It was designed and developed for use in Mediterranean streams in Spain (Munné and others 2003). The index is based upon four main aspects of the riparian area being studied, and unlike indices currently in use which assess the water quality itself or the habitat directly

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adjacent to the stream, the QBR index assesses a site's entire floodplain. It generates a score that can then be used to contrast sites, to compare sites to ideal conditions, or to assess the success of restoration projects over time.

In this study, we adapted the QBR index for use in central Ohio watersheds. The following specific objectives for the project are:

1. Alteration of any terms and requirements of the index that are region-specific to the Mediterranean area
2. Development of lists of native and non-native trees and shrubs found in central Ohio
3. Testing of the adapted index in three central Ohio watersheds: the Big Darby, Little Darby, and Walnut Creeks
4. Assessment of the usefulness of the adapted index in watershed management and planning

STUDY AREAS

Three central Ohio watersheds—Big Darby Creek, the Little Darby Creek, and the Walnut Creek—were used to test the adaptation of the QBR index. The Big Darby and the Little Darby are both State and National Scenic Rivers, and have exceptional water quality in large portions of the watersheds. Walnut Creek is also a stream of high water quality. All three watersheds provide habitat to a wide range of species including fish, macroinvertebrates, mussels, amphibians, mammals, and birds. Land ownership along these streams is a mix of private and public entities. The Columbus Metro Parks is one of the public landowners.

Twenty forested sites were chosen within each of these watersheds. Only sites with trees (either a forested area or a buffer) were chosen since the QBR index assesses the habitat quality of riparian forests. Sites were chosen to capture the range of forest area from sites with only a strip of trees on one stream bank to sites located within a continuous forest.

Because recent political and environmental activities along the Darby Creeks, access to the creeks has become limited, therefore, only portions of the watersheds could be sampled. Sites were thus chosen in these watersheds based on landowner approval and accessibility to the creeks. Sampling in the Walnut Creek watershed was conducted with fewer restrictions, as the work was conducted in conjunction with the stream quality monitoring by the Ohio Environmental Protection Agency (OEPA). Study sites in this watershed were chosen by the OEPA based on the amount of land area that is drained at each point along the length of the main stream and its tributaries.

METHODS

The QBR index developed by Munné and others (2003) was created for assessing the riparian forests of Mediterranean area streams. Several changes, therefore, were needed to make it applicable to the riparian forests of central Ohio streams. All of the components of the index were evaluated to determine whether the scoring requirements were adequate as they were originally developed, or whether they needed to be altered to more accurately reflect the quality of the riparian forests in central Ohio based on a search of the literature. If any part of the index was found to need revision, another literature review was then conducted to determine how the section could be modified to more accurately reflect the local conditions and relationships.

Once the components of the index were altered, it was tested in the three separate watersheds to determine whether or not the modifications accurately reflected the quality of central Ohio riparian forests. Within each of these watersheds, 20 study sites were chosen, resulting in a total sample of 60 sites. Sample sites in the Walnut Creek watershed were chosen from the study plan created by the OEPA for its stream quality monitoring, and were sampled during the summer of 2005 water quality testing. Sites within the Big and Little Darby watersheds were chosen based on accessibility of the creek and adjacent forests.

Each study site was centered on the streambed and was 50 meters in length following the stream channel. The width was variable, extending through the riparian forest to the edge of the floodplain. Floodplain width was based on the bank topography, position of terraces or dikes, and presence of piles of debris left by previous flooding, as well as through plant indicator species. In areas with a narrow riparian forest corridor, the forest edge itself was taken to be the edge of the floodplain for the purposes of this study.

After each site location was chosen, the 50-meter length measured upstream and the edge of the floodplain marked out, the QBR index was completed. This work was done in four parts following the four sections of the field sheet. Each part was assessed separately, and then all were combined at the end for scoring purposes (see Appendix). All field work was conducted during the summer of 2005, following the methodology of Munné and others (2003) after the leaf flush of the trees was finished and before the leaves started falling. Cover conditions, therefore, were relatively similar for all measurement periods.

After the field work was completed, we used the original QBR index to assess the data collected at all of the study sites for this project, and these results were compared with the results scored in the field. A one-way ANOVA was then run, comparing the final scores from each of the three watersheds to determine whether any statistical difference exists between them. The alpha level was set at 0.05, with a sample size (n) of three.

RESULTS

Alterations to the QBR Index

Several changes to the original QBR index were needed to adapt it to central Ohio riparian forests. Section one of the field sheet was the only section to remain the same in the altered index as in the original QBR. All three of the other sections were at least slightly altered to reflect the differences between the floodplains of Spain's Mediterranean streams and those of the streams of central Ohio.

The minor changes made to the second section of the index were needed to clarify the application of the index in the field. For the amount of tree and shrub cover, the numbers in the scoring were changed from 10-25 percent to 10-24 percent, since 25 percent was also included in the category above this one. A similar change was made to the part of section two dealing with the helophyte and shrub edge cover. Also in this section, in the component dealing with the distribution of trees and shrubland cover, the second scoring category was changed to shrubland of <50 percent, since 50 percent was not included in either option.

The third section of the index had the most important changes among all of the sections. The first change made to this section was to adjust the number of species required for each habitat type and score (Table 1). The number of tree species required was changed from the original numbers presented by Munné and others (2003) to double that number for the adapted index for central Ohio. Also in this section, the number of shrub species was increased to reflect the difference in species richness between Mediterranean Spain and central Ohio. The next change in section three of the index was to remove the gallery structure

Table 1.—Stream types and characteristics used in section 3 of the QBR index and native species requirements for scoring purposes in section 3 of the QBR index

Stream Type	Type 1	Type 2	Type 3
Characteristics	Closed riparian habitats. Riparian trees, if present, reduced to small strip. Headwaters.	Headwaters or midland riparian habitats. Forests may be large. First or second order streams.	Large riparian habitats. Potentially extensive forests. Third or higher order streams.
Minimum no. of species	>2	2	1
Middle no. of species	>4	4	3
Maximum no. of species	>6	6	5
No. of shrubs	>3	>4	>5

of the scoring for the riparian area because this structure did not apply to central Ohio. Finally in section three, the negative scoring for the presence of non-native trees was changed to apply to non-native shrubs as well.

In the fourth section of the index, changes were made to the scoring requirements for modifications of the channel. The scores given by Munné and others (2003) in the original index were kept, but factors contributing to that score were changed to require that both stream banks be modified to receive these scores. New categories were added to include sample sites with only one bank modified. The first category created was "fluvial terrace on one bank modified and constraining river channel" with an associated score of 15. The second category created was "channel modified by rigid structures along one margin" with an associated score of 10.

Minor changes were also made in this section concerning the riparian habitat type and were similar to the changes made in section two. The width of the islands categories were changed so that the first option included 5 meters, as the original options were greater than 5 meters and less than 5 meters. The percentage classes for the hard substrata were also changed to clarify which class each measurement belonged to as the classes overlapped. All scores associated with these classes remained the same.

The final changes made to the index were format changes. The setup of the field sheet was altered and locations to record species and to take notes were added. All of these changes were made to make the field sheet easier both to follow and to complete.

Comparison of the Original and Adapted QBR Indices

Scores from each site were computed for both the original index as created by Munné and others (2003) and for the adapted index. Some differences were found between the scores. Of the 60 sites, two scored higher with the adapted index and four scored lower with the adapted index. All other sites received the same score with both indices. Of the six sites with varying scores, only one was placed in a higher habitat quality class when the adapted index was used.

The sections of the index with the most variability in scores between the original and the adapted index were sections three and four. Several sites received higher scores with the adapted index due to the addition

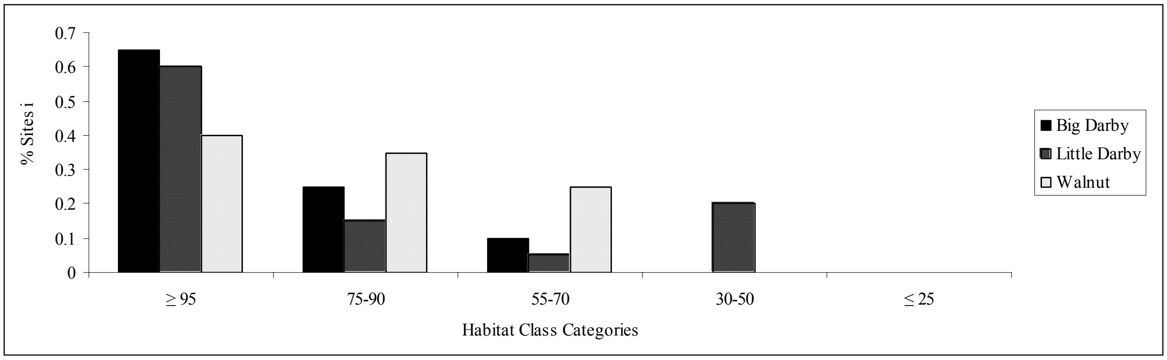

Figure 1.—Percentage of study sites in central Ohio within each score category by watershed.

of score classes in section four if only one side of the stream channel was altered. One site, however, received a lower score with the adapted index due to the changes in the number of tree and shrub species. Other sites also received lower scores due to the addition of non-native shrubs to the non-native trees category.

Riparian Forest Habitat Quality

Overall, site scores with the adapted index ranged from 45 to 100 (Fig. 1), compared to scores from 50 to 100 with the original index. No statistical differences were determined between the habitat qualities within the three watersheds (F=0.94, P=0.397). For both indices, individual section scores ranged from zero to 25, with many of the sections scoring beyond these set limits. These additional and negative points in the sections contributed to various sites' scores, but were not counted because the index is required to give each section an equal weight in the overall score.

No sites were in the very poor habitat class, and only four sites, all within the Little Darby watershed in highly agricultural areas, were in the poor quality class. Most sites, however, were in the fair, good, or excellent habitat quality classes (Table 2). All of the sample sites studied were of the second or third habitat types, which are characterized by having wider floodplains.

Section one was usually the lowest scoring section of the index. These scores ranged from zero to 25. The scores for section two of the adapted QBR Index were generally higher than those of section one. Scores for this section ranged from five to 25. The third section of the index had the highest scores for all three watersheds. The baseline score for section three was based on the native tree species richness. Richness was generally relatively high in all three watersheds. Section four of the index also ranged from zero to 25 points. All of the sites scored zero in the agricultural areas of the Little Darby watershed.

Table 2.—Classes of habitat quality and associated scores required from the QBR index.

Riparian Habitat Class	QBR Score
Riparian habitat in natural condition, excellent quality	≥95
Some disturbance, good quality	75-90
Disturbance important, fair quality	55-70
Strong alteration, poor quality	30-50
Extreme degradation, very poor quality	≤25

DISCUSSION

Alterations to the QBR Index

The changes made to the original QBR index did not result in major changes to the scores of the sites utilized in this study, indicating that some of the indicators of riparian forest habitats in the QBR index may be applicable to riparian forests in many different areas. The changes, however, resulted in a better reflection of the habitat quality when the individual components were assessed. The number of native species required in the third section of the index was increased to reflect the differences between the native tree and shrub diversity in Spain and that of the United States. Even with this increase in the number required, only one site had less than the number of tree species needed for the maximum points for the score of that section. The increase in the number of shrub species appears to be a needed increase since eleven of the total sites had the minimum number of species required for the extra points to section three's scores.

The other changes also appear to be supported by the data collected in the field testing. No sites were found to be structured in a gallery, so the removal of this portion of the index did not affect the overall scores of the index. The change in scoring from having both stream banks modified to having one or both modified reflected more accurately the available habitat and establishment area for trees and shrubs when only one bank is modified as opposed to those sites with both banks modified. Changing the category of non-native trees to non-native trees and shrubs was needed since only one non-native tree species was recorded in the study area, but four non-native shrub species were found, as opposed to no native shrub species in the study by Munné and others (2003). This component of the index is important in central Ohio where bush honeysuckle (*Lonicera maackii*) is present in the many human-disturbed ecosystems.

Even with the changes to the original index, no sites in any of the watersheds were scored in the poor or very poor habitat classes. The omission of these classes prevents a complete analysis of the adaptation of the index to central Ohio. It is unknown how well this index will assess riparian forests in these classes. We do not know whether the index scores all sites high, resulting in more sites in the upper classes and few or no sites in the lower classes.

All of the changes made to the index, however, appear to be supported by the field testing. The adapted index appears to be a more accurate reflection of the habitat quality in central Ohio riparian forests than the original index. The QBR index, as developed by Munné and others (2003), provided the basic guidelines in determining habitat quality for the sections of riparian forest under study. Further studies, though, are needed to test the index in the poorer habitat quality classes.

Riparian Forest Habitat Quality

Although the results of the one-way ANOVA indicated no statistical differences between the riparian forest habitat qualities of the three study watersheds, the Big Darby Creek watershed had the most sites in the excellent habitat quality class. The Little Darby Creek and the Walnut Creek watershed had fewer sites in the excellent habitat quality class. These trends were anticipated at the beginning of the study, since the Darby Watersheds are National and State Scenic Rivers, and the Big Darby is known for high water quality. In many areas, the riparian forest has been preserved and has been left intact along the stream banks. We did not expect, however, to find significant differences among the three watersheds.

Differences between the watersheds may be detected, however, if the portions of the watersheds where there are no riparian forests are included in the overall comparisons. Since this study focused only on the forested portions of the watersheds, the entire watershed was not included in the final analysis.

Management Implications

The QBR index provides a basic habitat quality value for a sample site. The results obtained from the testing of the index could be utilized in several ways. Most of the study sites in the study watersheds scored relatively high, indicating that further studies are needed in the lower range of the index. The high scoring in these streams may indicate that these are areas where conservation efforts should be directed; in several cases, conservation efforts already have been directed to these areas. Those sites that did not score in the excellent habitat quality class could be areas where management measures could be concentrated to improve the habitat over the whole watershed.

This index may also allow watershed managers to determine which attributes of the riparian forest are the most limiting factors for habitat. Most sites sampled that obtained less than excellent scores received lower scores because of reduced riparian and tree cover and reduced connectivity with adjacent woodlots. Improving the habitat quality by increasing cover requires planning, funding, and time. Plantings could increase cover in some of these areas, but it would take years to increase the tree cover. Given time and good management planning, however, the riparian forest habitat quality may be increased.

In other watersheds, this index could be used in restoration projects to follow the succession of forests as they mature. By using this index every 5 to 10 years, the changes in these areas could be determined and documented. The limiting components of the forests would also be assessed, and as needed, changes could be made to the management plans for the area to account for and improve any deficiencies in the riparian areas.

The QBR index also shows that it is possible for a methodology applied to a specific habitat type in one part of the world to be used in other parts of the world. This index was relatively easy to adapt for use in Ohio, and there may be other indices and methods from specific regions in the world that can be modified fairly easily to be applicable elsewhere.

CONCLUSIONS

The QBR index is needed in central Ohio for several reasons. There currently is no method for assessing the habitat quality of riparian forests based on direct measurements of the forest characteristics themselves. Although there are several indices for assessing the quality of riparian areas such as the qualitative habitat evaluation index (QHEI) and the vegetation index of biotic integrity (VIBI) for wetlands, the QHEI does not directly measure the characteristics of the riparian forest area. The riparian zone is only one of six characteristics studied in the QHEI. This index measures the width of the riparian vegetation, which includes not only forests but also grasslands, the floodplain quality, which is a recording of the type of habitat present along each stream bank, and erosion of the stream banks. On the other hand, the VIBI is used only for wetlands. Although wetlands are included in the scoring requirements of the QBR index, they are not the only portion of the riparian forest area studied.

Riparian forests are some of the most diverse habitat types in Ohio, with high species richness and many important functions in ecosystem processes (Innis and others 2000). They are also some of the most endangered ecosystems in the world today. The QBR index is a method for assessing the habitat quality of riparian forests. This index may be used to assess the current quality of riparian forests, and it may also be used to follow the progress of restoration projects in riparian areas. It could also be used, with careful planning and considerations, to determine areas in a watershed that need the most attention, and to allocate funds for improving the riparian forests and water quality.

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Appendix: Front Page of the Scoring Sheet for the QBR Index

Location: ___________________________ RM: ___________ Date: _____________

Observer(s): ________________________________ Time Sampled: _____________

Score of each section cannot be negative or exceed 25 points

Section 1: Total Riparian Cover

Score	*Riparian Cover Includes Trees, Shrubs, and Helophytes, but not Annuals*
25	>80% of riparian cover (excluding annual plants)
10	50 - 80% of riparian cover
5	10 -50% of riparian cover
0	<10% of riparian cover
+10 +5	If connectivity between riparian forest and adjacent woodland total If the connectivity is higher than 50%
-5 -10	If the connectivity is between 25 - 50% If the connectivity is <25%
	Total Score for Section 1

Section 2: Cover Structure

25	>75% of tree cover
10	50-75% of tree cover or 25-50% of tree cover but 25% shrub cover
5	Tree cover <50% but shrub cover between 10 - 25%
0	<10% of either tree or shrub cover
+10 +5 +5	At least 50% of channel has helophytes or shrubs If 25 - 50% of channel has helophytes or shrubs If trees and shrubs are in the same patches
-5 -5 -10	If trees are regularly distributed, and shrubland is >50% If trees and shrubs are in separate patches, without continuity Trees are distributed regularly, and shrubland is <50%
	Total Score for Section 2

Section 3: Cover Quality (based on geomorphological type)

	Type	1	2	3
25	Number of native tree species	>2	>4	>6
10	Number of native tree species	2	4	6
5	Number of native tree species	1	≤3	≤5
0	Absence of native tree species			
+10 +5 +5	If tree community is continuous along river and covers ≥75% of the edge riparian area Tree community is nearly continuous and covers at least 50% of the riparian area When the number of shrub species is	>3	>4	>5
-5 -5 -10 -10	If there are some man-made buildings in the riparian area If there are some isolated species of non-native trees/shrubs Presence of communities of non-native trees/shrubs Presence of garbage			
	Total Score for Section 3			

Section 4: Channel Alteration

25	Unmodified river channel
10	Fluvial terraces modified and constraining river channel
5	Channel modified by rigid structures along the margin
0	Channelized river
-10 -10	River bed with rigid structures (e.g., wells) Transverse structures into the channel (e.g., weirs or river crossings)
	Total Score for Section 4

	Final QBR Index Score (Sum of all four sections)

DOMINANT HEIGHT-BASED HEIGHT-DIAMETER EQUATIONS FOR TREES IN SOUTHERN INDIANA

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Abstract.—Height-diameter equations are developed based on dominant tree data collected in 1986 in 8- to 17-year-old clearcuts and the phase 2 Forest Inventory and Analysis plots on the Hoosier National Forest in south central Indiana. Two equation forms are explored: the basic, three-parameter Chapman-Richards function, and a modification of the three-parameter equation incorporating dominant canopy height as a surrogate variable for stand age and site quality. For most species or species groups, the modified equation provided a better fit to the height-diameter data than the standard form. Data from two follow-up studies in clearcuts collected between 2003 and 2006 were used to assess performance of the height-diameter equations. In general, the equations performed very well in terms of reflecting field assessed canopy class. In terms of predicting dominant canopy height, predicted tree heights overestimated dominant height relative to dominant height measured in the field; however, predicted heights for measured crop trees in the thinning trial were less than field measurements.

INTRODUCTION

Indiana is thought to have some of the most productive forest lands in the Central United States (Schmidt and others 1998). Indiana forests average 110 m^3ha^{-1} standing growing stock volume and have an average annual growth rate of 3.6 $m^3ha^{-1}year^{-1}$, the highest of any State in the former North Central Region (Shifley and Sullivan 2002).

Much of the land that comprises the Hoosier National Forest (HNF) was acquired in the 1930s following land abandonment (Leatherberry 2003). Many current stand structures that characterize the HNF, and much of southern Indiana, are the result of recolonization of abandoned fields and pastures or are heavily influenced by past human-induced disturbances including frequent burning, grazing of livestock, and repeated firewood cutting and/or high-grade lumbering (DenUyl 1954, Jenkins and Parker 2000). Productivity values in these stands often reflect low stocking, poor quality, and degraded stand structures (Schnur 1937), while well stocked stands regenerating following clearcutting, composed primarily of sprouts and seedlings, are considered to be more indicative of production capacity and site quality (Schnur 1937, Standiford and Fischer 1984).

From the mid-1960s to the mid-1980s, the HNF used clearcut harvesting to regenerate maturing stands, with the primary objective of regenerating oak and hickory species. In 1986, a study examining species response to clearcutting of the HNF was initiated (Fischer 1987, Fischer and others 1987, George and Fischer 1989). Stands sampled in 1986 were resampled between 2003 and 2005 (Kershaw and others

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2006). This pair of studies provides a unique opportunity to look at both stand dynamics and production relationships in young upland hardwood stands over a relatively long time period (Morrissey and others, in review).

One limitation of both studies is a lack of individual stem height data. Height measurements, especially in the Central Hardwood Region, are not often made. Reasons for the lack of height measurement include: 1) time required to complete measurements; 2) chance of observer error; and 3) visual obstructions (Colbert and others 2002). These limitations are especially true in regenerating and self-thinning cutover stands, where stem densities are quite high, and other obstructions, such as briars and grapevines, are abundant.

On the other hand, accurate estimates of height are crucial for estimating individual tree volume and stand productivity (Husch and others 2003). Existing height-diameter equations are either local in nature or were developed for mature stands (e.g., Colbert and others 2002, Lootens and others 2007). Application of these equations to young stands may not reflect the dynamic height-diameter relationship in young stands, especially self-thinning stands. The objectives of this paper are to: 1) develop a set of flexible polymorphic height-diameter equations for upland hardwood species in southern Indiana; and 2) test the applicability of these equations for estimating heights in self-thinning upland hardwood stands.

STUDY SITES

This study was conducted on the HNF in south-central Indiana. The HNF is located within the Highland Rim and Shawnee Hills Sections of the Interior Low Plateau (Homoya and others 1985). The 80,000-ha forest is administratively divided between the Brownstown Ranger District, and the Tell City Ranger District, which is composed of the Patoka Lake and Tell City management units.

Seventy-four naturally regenerated clearcut stands on the HNF were selected for measurement in 1986. Initially, all clearcuts made prior to 1982 were considered. The initial list was reduced to those stands with complete management records. The list of available stands was sorted by ranger district, management unit, and stand age. A sorted list by stand age within each ranger district was used to select sample stands. Stands were systematically selected from each list (Brownstown and Tell City) and placed in a queue. Stands were sequentially selected from the queue until the end of the field season.

1986 Sample Design

Sampling was conducted between July 1986 and March 1987. The boundary of each stand was traversed prior to sampling to insure map accuracy and to determine orientation of sample grids. The sample grid in each stand was oriented to insure a distribution of sample points across the range of slope and aspects present. Grid azimuths were determined from stand maps using a compass. An initial sample point was selected and plots were spaced 63.5 m apart following the sample grid (2.5 plots/ha). Distances were determined using pacing and azimuths were followed using a hand compass; approximate locations were marked on stand maps by hand. Measurement plots were 0.004-ha circular plots with a radius of 3.6 m. Plots falling partially into adjacent stands were not sampled.

At each plot center, average canopy height and other plot-level factors were measured. All trees and woody shrubs greater than 1.37 m in height were tallied by species (see Table 1 for a list of common and scientific names), crown class, and origin (seedling, seedling sprout, stump sprout, or residual). Species of the dominant plot tree (tallest plot tree) and the largest oak tree (by diameter at breast height [d.b.h.])

Table 1.—Mean and range of individual tree measurements by species group, individual species and data source (1986 clearcut study or FIA plots) for the predominant species groups on the Hoosier National Forest, Indiana. Clearcut data are the dominant plot tree data. FIA data are from the Phase II subplots. Nomenclature is based on the USDA, Plants database (http://plants.usda.gov/).

Species		1986 Clearcut Study							FIA Plots						
Common Name	Scientific Name	Number	d.b.h. (cm)			Height (m)			Number	d.b.h. (cm)			Height (m)		
			minimum	mean	maximum	minimum	mean	maximum		minimum	mean	maximum	minimum	mean	maximum
Oak	*Quercus* L.														
white oak	*Q. alba* L.	46	2.5	8.53	15.5	3.0	8.60	14.6	181	12.7	34.10	76.0	9.8	23.90	40.2
northern red oak	*Q. rubra* L.	56	1.8	7.54	14.5	3.7	8.42	13.4	33	13.5	39.08	72.4	13.1	26.79	38.7
black oak	*Q. velutina* Lam.	112	2.3	7.92	20.1	3.7	8.99	18.3	67	13.2	32.03	59.2	9.1	23.76	37.8
chestnut oak	*Q. prinus* L.	68	2.5	8.87	19.6	4.9	9.76	15.2	58	15.2	32.13	56.6	14.6	24.14	32.3
chinkapin oak	*Q. muehlenbergii* Engelm.	17	1.5	8.72	20.6	2.4	10.07	15.8	9	13.0	23.17	43.7	13.4	18.93	25.0
pin oak	*Q. palustris* Muenchh.	0		---			---		1		53.30			34.40	
post oak	*Q. stellata* Wangenh.	0		---			---		6	24.6	34.59	46.0	17.7	22.50	28.3
scarlet oak	*Q. coccinea* Muenchh.	5	9.7	12.44	16.0	7.3	10.36	14.6	28	15.2	34.44	55.6	13.1	25.68	32.9
shingle oak	*Q. imbricaria* Michx.	0		---			---		1		54.90			33.20	
Shumard oak	*Q. shumardii* Buckl.	3	1.8	3.50	6.9	2.4	3.63	5.5	2	39.4	42.42	45.5	26.8	27.13	27.4
Hickory	Carya Nutt.														
shagbark hickory	*C. ovata* (P. Mill.) K. Koch	3	5.3	5.83	6.1	4.9	6.10	7.9	21	13.5	24.66	49.0	12.5	21.55	28.6
pignut hickory	*C. glabra* (P. Mill.) Sweet	2	5.1	8.15	11.2	6.1	7.30	8.5	68	13.7	29.54	53.3	13.4	24.57	35.0
bitternut hickory	*C. cordiformis* (Wangenh.) K. Koch	4	4.6	7.82	12.7	4.9	7.78	10.4	12	19.3	30.42	45.0	18.3	26.34	39.3
mockernut hickory	*C. alba* (L.) Nutt. ex Ell.	1		3.30			4.30		0		---			---	
shellbark hickory	*C. laciniosa* (Michx. f.) G. Don	3	5.3	5.83	6.1	4.9	6.10	7.9	21	13.5	24.66	49.0	12.5	21.55	28.6
Yellow-Poplar	*Liriodendron tulipifera* L.	538	2.0	10.45	25.1	2.4	10.85	20.7	83	13.2	29.99	74.7	10.0	23.31	38.4
Black Cherry	*Prunus serotina* Ehrh.	269	1.0	10.24	24.4	2.4	9.71	18.9	23	3.0	19.28	36.6	4.0	16.82	22.9
Maple	*Acer* L.														
sugar maple	*Acer saccharum* Marsh.	63	1.0	6.80	15.2	3.0	7.92	12.8	181	12.7	22.40	70.9	8.8	19.24	38.1
red maple	*Acer rubrum* L.	66	3.0	8.43	16.0	3.7	9.34	15.2	96	12.7	22.31	51.0	11.9	19.76	32.6
boxelder	*Acer negundo* L.	0		---			---		2	19.0	20.07	21.1	15.8	16.61	17.4
Ash	*Fraxinus* L.														
white ash	*Fraxinus americana* L.	89	1.5	7.46	15.7	1.8	7.39	17.1	50	12.7	24.28	48.8	11.0	20.64	34.1
green ash	*Fraxinus pennsylvanica* Marsh.	0		---			---		1		29.20			14.63	
Elm	*Ulmus* L.														
American elm	*Ulmus americana* L.	7	5.1	10.60	17.8	4.9	7.74	11.6	19	12.7	19.94	36.8	11.9	16.14	24.1
red elm/slippery elm	*Ulmus rubra* Muhl.	108	1.5	9.40	16.8	3.0	9.41	16.5	7	14.0	20.83	31.2	14.6	19.16	26.2
winged elm	*Ulmus alata* Michx.	3	2.0	4.80	8.6	3.0	5.27	8.5	5	13.7	16.61	18.5	12.2	14.32	15.5
Siberian elm	*Ulmus pumila* L.	0		---			---		1		20.60			19.20	
ironwood/hophornbeam	*Ostrya virginiana* (P. Mill.) K. Koch	3	3.3	4.63	6.3	6.7	7.93	9.8	1		14.00			13.70	
bluebeech/hornbeam	*Carpinus caroliniana* Walt.	0		---			---		1		13.50			10.00	
Walnut	*Juglans* L.														
black walnut	*Juglans nigra* L.	7	5.1	10.13	17.0	3.7	7.84	11.6	11	13.5	24.59	40.1	8.5	21.58	29.9
butternut	*Juglans cinerea* L.	6	7.6	10.68	14.5	7.9	9.75	11.6	1		21.30			8.80	
Other Tree Species															
sassafras	*Sassafras albidum* (Nutt.) Nees	112	1.0	7.43	20.8	3.0	8.57	20.7	54	12.7	19.24	51.8	11.6	18.78	29.0
aspen	*Populus grandidentata* Michx.	96	2.5	11.22	23.9	4.3	12.92	20.7	11	26.2	31.86	43.9	25.0	29.98	32.0
American beech	*Fagus grandifolia*	4	4.3	7.55	11.4	3.7	6.88	12.2	40	13.2	25.74	66.8	10.4	19.51	33.8
blackgum	*Nyssa sylvatica* Marsh.	17	0.8	5.98	12.4	1.8	6.69	18.3	40	12.7	18.50	38.4	10.0	15.64	22.2
sycamore	*Platanus occidentalis* L.	16	2.0	9.21	18.3	3.7	9.74	14.6	13	14.5	34.35	53.8	12.8	23.56	36.0
black locust	*Robinia pseudoacacia* L.	15	5.6	8.79	12.7	5.5	7.87	12.8	9	14.2	17.41	24.4	11.9	15.78	25.9
American chestnut	*Castanea dentata* (Marsh.) Borkh.	1		11.20			8.50		0		---			---	
basswood	*Tilia americana* L.	8	2.5	9.85	12.7	6.1	10.44	15.2	0		---			---	
hackberry	*Celtis occidentalis* L.	1		9.10			7.30		1		31.80			25.90	
honeylocust	*Gleditsia triacanthos* L.	0		---			---		1		23.10			17.40	
persimmon	*Diospyros virginiana* L.	0		---			---		2	13.5	15.50	17.5	14.6	15.85	17.1
river birch	*Betula nigra* L.	0		---			---		2	26.4	27.18	27.9	15.2	17.37	19.5
sweetgum	*Liquidambar styraciflua* L.	0		---			---		1		27.40			28.00	
European alder	*Alnus glutinosa* (L.) Gaertn.	0		---			---		1		16.00			14.00	
Softwood Species															
eastern redcedar	*Juniperus virginiana* L.	0		---			---		53	12.7	19.98	47.0	5.8	12.53	22.2
eastern white pine	*Pinus strobus* L.	0		---			---		62	12.7	24.83	58.4	8.5	17.43	32.0
shortleaf pine	*Pinus echinata* P. Mill.	0		---			---		77	14.2	29.07	47.2	12.5	23.48	32.3
virginia pine	*Pinus virginiana* P. Mill.	0		---			---		17	12.7	18.59	25.4	13.1	16.55	22.9
Understory Woody Species															
dogwood	*Cornus florida* L.	0		---			---		7	4.8	10.56	18.5	4.3	7.92	11.9
red bud	*Cercis canadensis* L.	4	2.8	4.55	6.6	3.0	4.28	5.5	4	13.0	13.78	16.3	6.4	9.98	11.6
willow	*Salix* (L.) spp	2	9.4	9.80	10.2	9.8	10.10	10.4	0		---			---	
sumac	*Rhus typhina* L.	2	3.3	3.55	3.8	3.7	5.20	6.7	0		---			---	
buckthorn	*Rhamnus cathartica* L.	1		5.30			6.70		0		---			---	
hoptree	*Ptelea trifoliata* L.	1		3.60			3.00		0		---			---	

were recorded and d.b.h. and total height measured. Data were recorded on field tally sheets and later keypunched. A total of 1,801 plots were established and measured. A complete description of sample plot location and all measurements is found in Fischer (1987) and George and Fischer (1989).

2003 Sample Design

Clearcut Follow-up Study

Only 70 of the original 74 stands selected in 1986 were available for sampling in 2003. Given time since the original study, technology used to initially establish field plots, and lack of permanent plot markers, no attempt was made to relocate the original 1986 plots.

Stands from the 1986 study were relocated and outlined using SOLO Field GPS software® (TDS, Corvallis, OR) to more accurately determine stand area. Sample plots were arranged on a 63.5 x 63.5 m grid (2.5 plots/ha) using SOLO Field GPS software, and permanent sample plot centers were established for future study. Each plot center was located using the SOLO Field GPS software, and plot centers were logged for future reference using latitude and longitude coordinates and elevation information. Each plot consisted of a 0.04-ha tree tally and a 0.004-ha reproduction plot.

Dominant height and other plot-level variables were recorded for each plot. One tree deemed to be representative of average dominant canopy height was selected and measured to the nearest 1.5 m using a clinometer. Within each 0.04-ha plot, all trees with a d.b.h. greater than 2.54 cm were tallied by species and measured using calipers. The d.b.h., crown class (dominant, intermediate, suppressed), and origin (sprout, seed) were recorded for each tree. Within each 0.004-ha plot, all trees less than 2.54 cm d.b.h. were tallied by species. A total of 1,330 plots were established and measured. A complete description of sample plot location and associated measurements is found in Kershaw and others (2006) and Morrissey (2006).

Thinning Trial

Five additional clearcut stands, similar in age to the ones described above, were selected for a thinning trial aimed at increasing the proportion of oak and hickory. In each stand, three 0.4-ha study plots were located and in each plot, 40 crop trees identified based on species (oak and hickory favored) and canopy class (dominant and codominant). Fifteen of the 40 crop trees in each plot were randomly selected and measured for total height, height to crown base, and crown width. The 225 measured crop trees were used to provide an independent test of the accuracy of the height-diameter equations developed in this study.

2005 FIA Plot Database

U.S. Forest Service Forest Inventory and Analysis (FIA) phase 2 plots located on the HNF were downloaded from the FIA online data server (http://fia.fs.fed.us/tools-data/tools/). Pertinent plot data and individual tree species, heights and d.b.h.s were extracted and imported into the R statistical software (R Development Core Team 2007). Plots from the full 2001-2005 measurement cycle were used.

METHODS

Individual species were grouped into 11 species groups (Table 1). Data from the 1986 clearcut sample were combined with FIA plot data located on the HNF to develop height-diameter equations on the basis of species groups and for more abundant individual species. These equations were validated using the 2003 clearcut studies. Table 1 contains a summary of the individual tree height and d.b.h. measurements by species and data source.

Height - Diameter Estimation

Height-Diameter Models

Several model forms are frequently used for estimating height-diameter relationships (Huang and others 2000, Trincado and Leal 2006). The basic 3-parameter form of the Chapman-Richards function (Clutter and others 1983) is utilized in this study:

[1] $$H = H_B + b_1 \bullet \left(1 - e^{-b_2 \bullet D}\right)^{b_3}$$

where H_B is breast height (1.37 m), H is total height, D is diameter at d.b.h., and b_i's are species-specific regression coefficients. This function was chosen because: 1) H = H_B when D = 0; 2) the function is simple, yet quite flexible in form; and 3) the parameters have reasonable biological interpretation.

The b_1 coefficient is the asymptotic maximum height. For a given species, this coefficient represents the theoretic maximum height obtainable. For a given stand or plot, this parameter could be used to represent maximum tree height. By modifying equation [1] so that b_1 changes as a function of stand age, site index, dominant height, or stand density, equation [1] can be generalized to be more applicable to a wider range of sites and stand ages, or more regionally applied (e.g., Arabatzis and Burkhart 1992, Trincado and Leal 2006).

Since dominant canopy height was available, or easily calculated, in all datasets, and can be used to reflect differences in stand age and site index, equation [1] was modified to include dominant canopy height:

[2] $$H = H_B + \left(c_1 \bullet H_{dom}^{c_2}\right) \bullet \left(1 - e^{-b_2 \bullet D}\right)^{b_3}$$

where H_B, H, and D are as above, H_{dom} is dominant canopy height, and the b_i's and c_i's are species-specific regression coefficients.

The combined 2005 FIA data and dominant tree data from 1986 were used to derive height-diameter equations. Dominant height was calculated for each FIA subplot. Dominant height was a measured variable on the 1986 plots.

Dominant heights on FIA plots were calculated using Gingrich's (1967) stocking equations. For each FIA subplot, the tree list was sorted from tallest to shortest tree. The stocking contribution of each tree was computed using the equation for the "B-line", which represents canopy closure. Stocking contributions were accumulated until full B-line level stocking (1000 milacres) was achieved. Average height of the tallest trees required to reach B-line stocking was calculated and used to represent dominant height.

Equations [1] and [2] were fitted to individual species data and to data grouped by genus or growth type (Table 1). For all species, equations were fitted using a nonlinear regression package in R (R Development Core Team 2007) with non-weighted and weighted fits. Best fit was determined on the basis of the lowest Furnival's (1961) Index (FI), residual distributions, and parameter estimates and their associated standard errors.

Model Validation

Data from the 2003 plots were used to validate the equations developed above. No individual tree height data were measured; however, dominant plot height and crown class (dominant, intermediate, and suppressed) of each tree were available. Individual tree heights were predicted using the species-specific coefficients, d.b.h, and dominant plot height. Relative height, calculated as the ratio of predicted tree height to maximum predicted tree height within each plot, was calculated. Histograms of the distributions of relative heights by species and crown class were used to visually assess model performance. Dominant height for each plot was then estimated using predicted individual tree heights and Gingrich's (1967) "B-line" stocking equation as described for the FIA plots. Estimated dominant heights were compared to dominant heights measured in the field. For the thinning trial data, heights of measured crop trees were compared to predicted heights based on the equations developed in this study.

RESULTS

Height-Diameter Equations

Model Fits

Table 2 shows estimated parameters, their associated standard errors, nonlinear pseudo r^2's (Kutner and others 2003), and FI by species group, individual species, and equation form (eqs. [1] and [2]). Non-weighted and weighted fits were compared on the basis of smallest FI. In general, optimal weight (smallest FI) was d.b.h.$^{-.5}$. For almost all species groups and individual species, equation [2], the equation incorporating dominant canopy height provided, a better fit to the height-diameter data than did the standard model (eq. [1]). Only shagbark hickory and blackgum had better associated fit statistics with equation [1] than equation [2].

For several species groups and individual species the shape (b_3) parameter was dropped from the equations (Table 2). Dropping the shape parameter reduces the three-parameter Chapman-Richards equation to the two-parameter formulation (Clutter and others 1983). For aspen, the exponential decay (b_2) parameter was fixed at a value of b_2 = .02. All attempts to obtain fits that met convergence criteria failed when b_2 was allowed to vary. The value of .02 was selected based on a grid search of values of b_2 (Kutner and others 2003).

Overall, both equations fitted the height-diameter data well (Table 2). Almost all pseudo r^2's (Kutner and others 2003) were greater than .50 and most were greater than .70 (29 of 33 species for eq. [1] and 31 of 33 for equation [2]). For equation [1], the shape parameter, b_3, was generally greater than 1.0, indicating a sigmodial-shaped height-diameter relationship. For equation [2], the shape parameter was generally less than 1.0, indicating an asymptotically increasing height-diameter relationship within a given dominant height level. Comparisons of estimated heights based on the two equations are shown in Figure 1 along with the FIA and clearcut data for four selected species. Within a given dominant canopy height class, resulting height-diameter curves were generally flatter than curves resulting from equation [1] (Fig. 1).

Validation of Height-Diameter Relationships

Figure 2 shows relative height distributions by canopy class for a selected set of species. A complete summary by crown class and species is shown in Table 3. For all species groups, mean relative height decreases from the dominant canopy class, to the intermediate canopy class, to the suppressed canopy class. While there is overlap between classes, the distributions of relative heights reflect the three canopy classes

Table 2.—Regression statistics, estimated coefficents, and standard errors (in parentheses) by species and height-diameter equation form (Standard, Eq. 1 and Dominant Height, Eq. 2)

Species		Standard[b]					Dominant Height[b]					
	N	r^2	FI[a]	b_1	b_2	b_3	r^2	FI[1]	c_1	c_2	b_2	b_3
Oak	693	0.92	2.58	34.826	0.037	1.111	0.95	**2.09**	11.832	0.374	0.013	0.510
				(1.029)	(.003)	(.049)			(1.189)	(.021)	(.004)	(.041)
white oak	227	0.88	2.86	31.945	0.048	1.343	0.92	**2.34**	9.187	0.385	0.031	0.760
				(1.195)	(.006)	(.138)			(1.239)	(.038)	(.007)	(.106)
red oak	89	0.94	2.43	37.982	0.033	1.107	0.97	**1.70**	9.196	0.482	0.007	0.388
				(2.798)	(.007)	(.107)			(3.547)	(.052)	(.011)	(.087)
black oak	179	0.93	2.26	38.205	0.031	1.051	0.96	**1.82**	11.764	0.397	0.011	0.475
				(2.871)	(.006)	(.082)			(2.994)	(.04)	(.009)	(.075)
chestnut oak	126	0.92	2.24	33.017	0.040	1.113	0.94	**1.91**	16.042	0.323	0.008	0.482
				(2.726)	(.009)	(.12)			(8.572)	(.049)	(.015)	(.113)
other oak species	72	0.90	2.90	34.128	0.038	1.104	0.94	**2.14**	6.848	0.427	0.066	---
				(4.007)	(.013)	(.204)			(1.513)	(.06)	(.008)	(---)
Hickory	110	0.81	3.12	34.140	0.051	1.379	0.84	**2.88**	10.029	0.370	0.040	0.970
				(2.885)	(.014)	(.301)			(3.198)	(.087)	(.018)	(.289)
shagbark hickory	24	0.88	**2.46**	27.451	0.090	2.077	0.88	2.52	28.262	-0.009	0.091	2.101
				(1.974)	(.025)	(.728)			(19.533)	(.209)	(.028)	(.946)
pignut hickory	70	0.73	3.22	34.735	0.046	1.229	0.77	**2.97**	8.070	0.412	0.055	1.230
				(4.973)	(.022)	(.448)			(3.658)	(.122)	(.026)	(.536)
bitternut hickory	16	0.93	2.93	196.808	0.004	0.922	0.95	**2.42**	14.992	0.364	0.023	---
				(1172.678)	(.029)	(.365)			(10.375)	(.152)	(.009)	(---)
Yellow Poplar	621	0.84	2.40	66.915	0.010	0.829	0.89	**2.00**	8.909	0.354	0.070	---
				(13.909)	(.004)	(.039)			(.664)	(.019)	(.004)	(---)
Black Cherry	292	0.68	2.21	127.857	0.003	0.774	0.80	**1.72**	6.003	0.401	0.083	0.714
				(522.805)	(.018)	(.104)			(.758)	(.029)	(.026)	(.13)
Maple	408	0.83	2.72	28.060	0.058	1.262	0.87	**2.41**	14.739	0.283	0.017	0.593
				(1.118)	(.007)	(.104)			(2.53)	(.028)	(.01)	(.08)
sugar maple	244	0.82	2.88	27.455	0.062	1.350	0.86	**2.54**	12.899	0.333	0.015	0.580
				(1.36)	(.01)	(.156)			(3.406)	(.041)	(.013)	(.109)
red maple	164	0.86	2.46	29.007	0.053	1.175	0.89	**2.14**	16.357	0.259	0.016	0.581
				(1.905)	(.01)	(.137)			(4.432)	(.037)	(.014)	(.111)
Ash	140	0.90	2.53	38.760	0.036	1.256	0.94	**2.02**	11.029	0.411	0.012	0.524
				(5.235)	(.01)	(.135)			(4.807)	(.049)	(.016)	(.119)
white ash	139	0.91	2.40	38.452	0.038	1.292	0.94	**1.98**	11.212	0.382	0.017	0.588
				(4.612)	(.009)	(.131)			(3.296)	(.05)	(.014)	(.123)
Elm[c]	157	0.78	2.12	37.886	0.025	0.988	0.82	**1.89**	17.816	0.265	0.010	0.546
				(14.795)	(.018)	(.153)			(18.403)	(.042)	(.026)	(.135)
American elm	26	0.78	2.47	26.226	0.053	1.375	0.83	**2.14**	11.595	0.235	0.050	---
				(8.695)	(.043)	(.685)			(4.502)	(.087)	(.016)	(---)
red elm/slippery elm	115	0.76	2.03	71.603	0.011	0.936	0.82	**1.77**	30.154	0.300	0.003	0.528
				(2.204)	(.048)	(.015)			(147.415)	(.048)	(.031)	(.14)
Walnut	25	0.80	3.62	56.173	0.021	1.200	0.84	**3.27**	12.509	0.309	0.038	---
				(71.35)	(.042)	(.594)			(8.565)	(.138)	(.02)	(---)
black walnut	18	0.86	3.41	32.934	0.062	1.938	0.92	**2.50**	6.882	0.452	0.055	---
				(8.66)	(.04)	(1.005)			(3.429)	(.123)	(.018)	(---)
Other Tree Species	433	0.81	2.85	33.174	0.038	1.061	0.83	**2.70**	19.996	0.186	0.021	0.680
				(2.16)	(.006)	(.076)			(2.802)	(.028)	(.008)	(.079)
sassafras	166	0.84	2.34	27.942	0.061	1.298	0.88	**1.98**	10.033	0.316	0.036	0.610
				(2.676)	(.013)	(.147)			(1.874)	(.041)	(.018)	(.121)
aspen	107	0.76	2.91	53.867	0.022	---	0.85	2.04	3.759	0.628	0.020	0.146
				(9.231)	(.005)	(---)			(.927)	(.058)	(---[d])	(.075)
American beech	44	0.78	3.17	27.261	0.070	1.700	0.81	**2.96**	9.587	0.324	0.050	1.111
				(1.974)	(.022)	(.608)			(4.177)	(.131)	(.026)	(.498)
blackgum	57	0.86	**2.11**	22.921	0.074	1.464	0.86	2.12	20.405	0.044	0.065	1.296
				(2.675)	(.023)	(.325)			(5.418)	(.093)	(.031)	(.47)
other misc. species	59	0.88	2.64	77.888	0.008	0.882	0.90	**2.51**	21.168	0.163	0.032	---
				(83.4)	(.015)	(.166)			(6.62)	(.064)	(.007)	(---)
Softwood Species	209	0.62	3.95	28.029	0.069	2.161	0.80	**2.84**	1.829	0.815	0.122	3.968
				(2.387)	(.019)	(.657)			(.369)	(.06)	(.019)	(1.18)
eastern redcedar	53	0.63	2.93	17.580	0.117	3.716	0.59	**2.42**	16.143	0.146	0.031	---
				(1.652)	(.042)	(2.245)			(10.589)	(.213)	(.009)	(---)
eastern white pine	62	0.74	3.01	49.071	0.016	---	0.80	**2.59**	10.142	0.462	0.019	0.959
				(11.981)	(.005)	(---)			(6.704)	(.095)	(.022)	(.321)
shortleaf pine	77	0.49	3.35	26.003	0.117	3.223	0.82	**1.98**	1.300	0.922	0.080	---
				(1.299)	(.042)	(2.331)			(.34)	(.077)	(.008)	(---)
Virginia pine	17	0.43	2.49	20.534	0.074	---	0.53	**1.96**	3.972	0.534	0.081	---
				(4.895)	(.038)	(---)			(2.23)	(.174)	(.03)	(---)
Understory Woody Species	15	0.89	1.15	24.398	0.035	1.084	0.89	**1.15**	24.507	0.045	0.026	---
				(47.004)	(.101)	(.579)			(31.487)	(.131)	(.033)	(---)

[a]Bolded FI indicates best fit

[b]italic parameter estimates indicate parameter estimates that are not significantly different from 0 at a=.05

[c]Elm species include all Ulmacea spp (*Ulmus, Ostrya*, and *Carpinus*)

[d]value of .02 fixed after grid search for "best" value, could not achieve convergence of full model

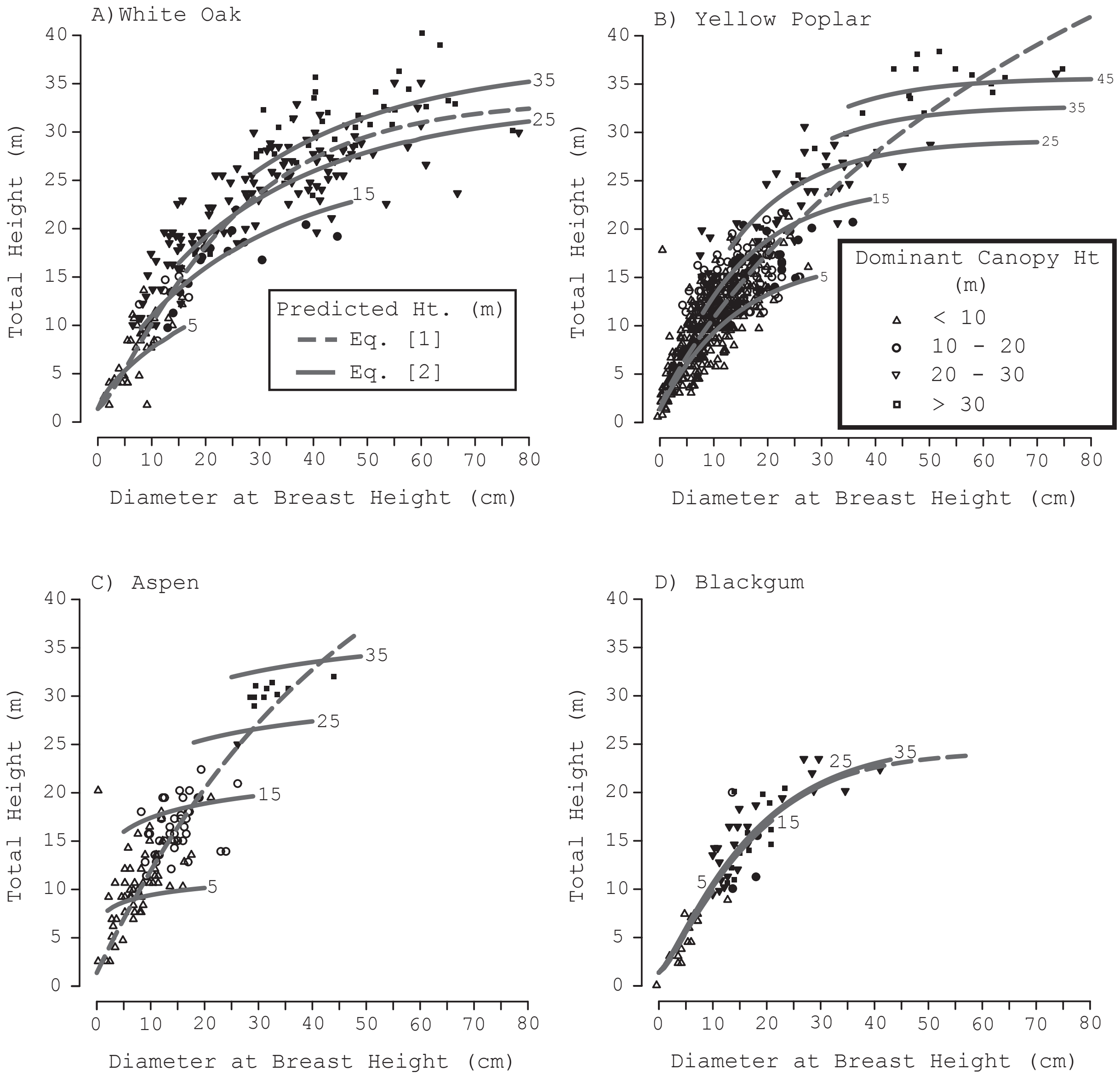

Figure 1.—Observed total height versus d.b.h. and predicted total height for equations [1] and [2] for selected species on the Hoosier National Forest: A) white oak, B) yellow-poplar, C) aspen, and D) blackgum.

very well (Table 3 and Fig. 2). Figure 3 shows the relationship between predicted dominant height, based on predicted heights and Gingrich's (1967) "B-line" stocking equation (as described above). Predicted dominant height was generally greater than dominant heights measured in the field. For the measured crop trees, heights were, on average, under-predicted (Table 4 and Fig. 4). For some species, especially white oak and red oak, heights were substantially under-predicted (> 1.5 m), while for most of the other species errors in height prediction were less than 1.0 m.

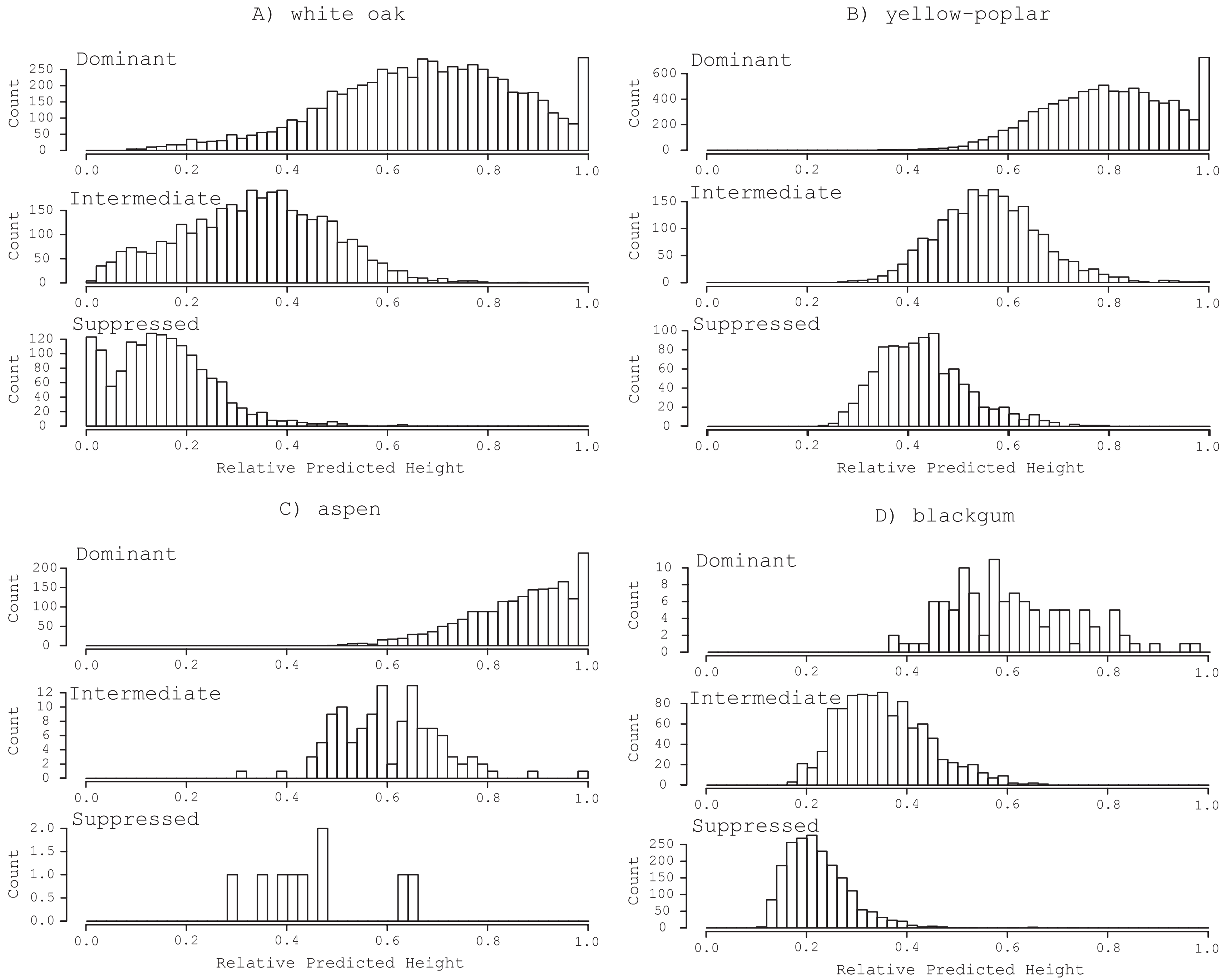

Figure 2.—Distribution of relative predict total heights by canopy class for selected species on the Hoosier National Forest: A) white oak, B) yellow-poplar, C) aspen, and D) blackgum.

Table 3.—Mean, standard deviation, and range (in parentheses) of relative tree heights by species group and canopy class for the 2003 clearcut samples from the Hoosier National Forest, Indiana

Species Group	Canopy Class					
	Dominant		Intermediate		Suppressed	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Oak	0.67	0.18	0.34	0.14	0.15	0.10
	(0.08, 1.00)		(0.01, 0.86)		(0.00, 0.64)	
Hickory	0.71	0.19	0.35	0.13	0.21	0.08
	(0.19, 1.00)		(0.03, 0.99)		(0.02, 0.58)	
Yellow-Poplar	0.80	0.12	0.56	0.10	0.43	0.09
	(0.35, 1.00)		(0.26, 1.00)		(0.23, 0.79)	
Black Cherry	0.76	0.14	0.51	0.12	0.36	0.12
	(0.33, 1.00)		(0.24, 1.00)		(0.16, 0.75)	
Maple	0.70	0.13	0.45	0.10	0.30	0.06
	(0.18, 1.00)		(0.07, 0.97)		(0.07, 0.73)	
Ash	0.69	0.13	0.45	0.10	0.30	0.08
	(0.32, 1.00)		(0.14, 1.00)		(0.15, 0.69)	
Elm	0.65	0.13	0.37	0.10	0.24	0.07
	(0.27, 1.00)		(0.14, 1.00)		(0.12, 0.71)	
Walnut	0.80	0.14	0.54	0.16	0.46	0.15
	(0.41, 1.00)		(0.29, 0.81)		(0.25, 0.79)	
Other Tree Species	0.74	0.15	0.46	0.12	0.24	0.09
	(0.27, 1.00)		(0.10, 1.00)		(0.08, 0.84)	
Softwood Species	0.68	0.18	0.36	0.14	0.21	0.10
	(0.26, 1.00)		(0.13, 0.70)		(0.03, 0.62)	
Understory Woody Species	0.46	0.10	0.33	0.09	0.21	0.06
	(0.25, 0.89)		(0.03, 0.75)		(0.08, 0.58)	

Table 4.—Prediction errors from the best fit equations applied to the crop tree measurements from the oak thinning study on the Hoosier National Forest, Indiana.

Species	Sample	Error		
	Size	Ave(Error)	Ave|Error|	rMSE
white oak	65	1.68	2.04	2.56
red oak	17	2.85	2.85	3.04
chestnut oak	24	-0.07	1.63	1.93
black oak	17	-1.15	1.95	2.71
scarlet oak	34	-0.03	1.55	2.31
shagbark hickory	3	0.43	2.32	2.76
pignut hickory	2	-1.25	1.25	1.27
bitternut hickory	1	6.43	6.43	6.43
yellow poplar	25	-0.82	1.45	1.79
black cherry	31	0.53	2.19	2.86
sugar maple	1	-0.47	0.47	0.47
black walnut	3	-0.26	1.62	1.72
white ash	2	0.24	0.24	0.24
Average	225	0.60	1.92	2.48

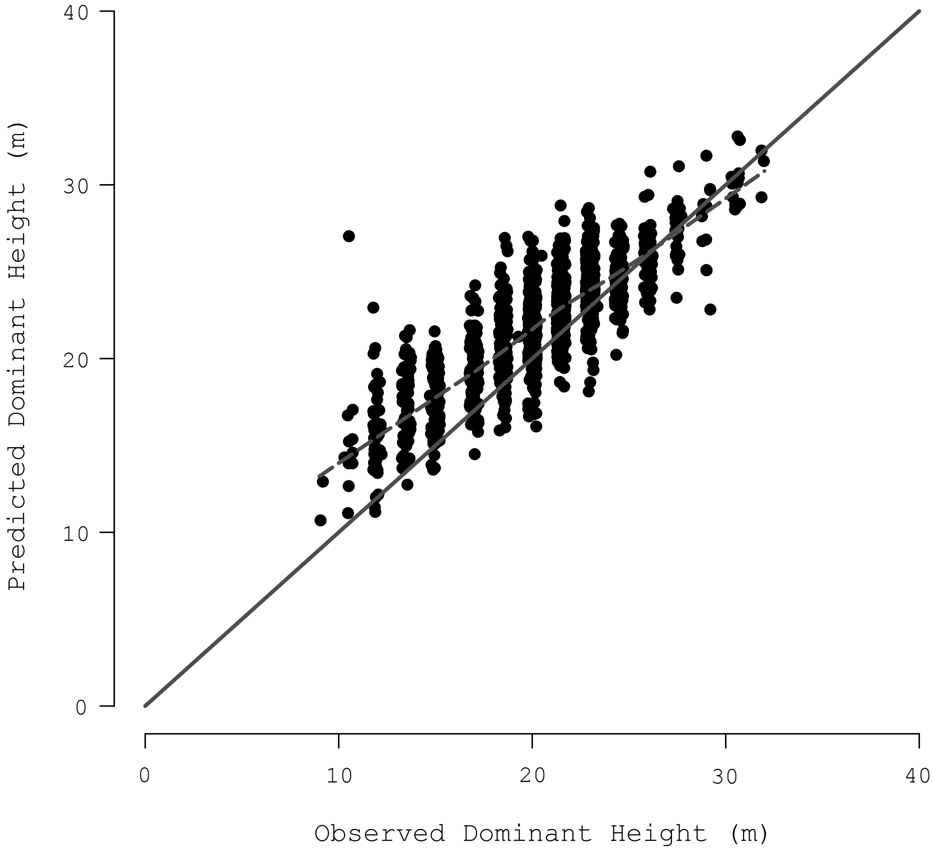

Figure 3.—Predicted versus observed dominant height for the 2003 clearcut plots on the Hoosier National Forest. Solid line is the 1:1 line and the dashed line is a lowess smoothed trend line.

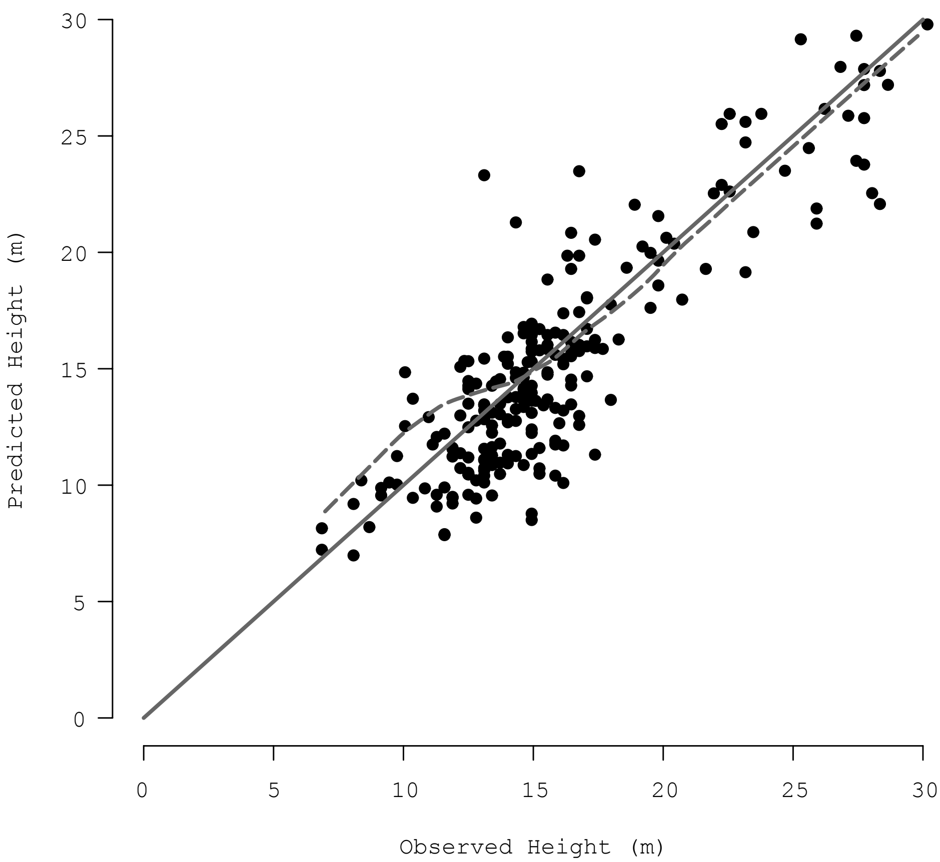

Figure 4.—Predicted versus observed heights for crop trees in the thnning trials on the Hoosier National Forest. Solid line is the 1:1 line and the dashed line is a lowess smoothed trend line.

DISCUSSION

Accurate height-diameter equations are a valuable tool for forest managers. While d.b.h. is easily and accurately measured, height is time consuming and prone to error (Arabatzis and Burkhart 1992, Colbert and others 2002, Trincado and Leal 2006). While several equation forms are frequently used (Huang and others 2000), many of these equations are applicable only to a limited geographic area or limited range of stand ages (Trincado and Leal 2006). As a result, height-diameter equations are often classified as local or general (Arabatzis and Burkhart 1992, Trincado and Leal 2006). General height-diameter equations typically modify a local equation by incorporating additional variables such as stand age, site index, dominant height, maximum height, or other stand structure variables (Huang and others 2000).

The equations developed here started with a local height-diameter equation (Eq. 1) and incorporated dominant height to produce a general height diameter equation (Eq. 2). The b_1 parameter in the local equation, which represents the asymptotic maximum height, was replaced by a power function of dominant height. With the exception of two species, shagbark hickory and blackgum, all species and species groups had better fits with equation 2 than equation 1 (Table 2). Several other researchers (e.g., Bi and others 2000, Diéguez-Aranda and others 200, Wang and Tang 1997) also found that incorporating dominant height into local height-diameter equations resulted in improved fits to data for several tree species; however, Arabatzis and Burkhart (1992) did not find that dominant height was as good as other stand parameters for modeling regional height-diameter relationships in loblolly pine. Leite and Andrade (2003) considered dominant height to be one of the fundamental structural variables in development of height-diameter equations.

Not only were fits improved in this study, resulting equation forms were altered (Fig. 1) by incorporating dominant height into the height-diameter relationship. For all species, the shape parameter (b_3) for equation 1 was greater than 1.0, producing a sigmodial shape height-diameter relationship. The shape parameter for equation 2 was generally smaller than 1.0 producing a monotonically increasing height-diameter relationship (Fig. 1). This change in shape is important to understand since the equations were developed across a wide range of tree and stand ages. For example, predicted heights for a 20-cm d.b.h. yellow-poplar (Fig. 1B) would be about 15 m and would increase to about 25 m for a 40-cm d.b.h. tree based on equation 1; however, using equation 2, the increase is much smaller within a given dominant height class (approximately 17 m to 20 m for a 15-m dominant height stand and 21 m to 25 m for a 25-m dominant height stand).

Dominant height, as incorporated into the height-diameter equations developed here, enables the asymptotic maximum height to change as stands develop. Biologically, it makes sense that asymptotic maximum height should be related to dominant canopy height, since dominant canopy height is the average of the dominant (i.e., tallest) trees in a stand. Others have used stand density measures (e.g., Sharma and Zhang 2004, Staudhammer and LeMay 2000) to represent this change. While these equations may work for relatively pure even-aged stands, it is unlikely that they would adequately represent the relationships observed in the mixed species stands that characterize the Central Hardwoods Region.

The equations developed here cover a broad range of tree sizes and stand ages. Even though the data came only from very young stands and older mature stands, they appear to adequately predict height-diameter relationships in self-thinning stands (Figs. 2, 3, and 4). These equations are an important first step in assessing changes in productivity following clearcutting in south central Indiana.

ACKNOWLEDGMENTS

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A GIS-BASED APPROACH TO STAND VISUALIZATION AND SPATIAL PATTERN ANALYSIS IN A MIXED HARDWOOD FOREST IN WEST VIRGINIA

Benktesh D. Sharma, Jingxin Wang, and Gary Miller[1]

Abstract.—Tree spatial patterns were characterized for a 75-year-old mixed hardwood forest dominated by northern red oak, chestnut oak, red maple and yellow-poplar. All trees ≥5 inches diameter at breast height (d.b.h.) were measured for diameter, total height, crown height, and crown width along with their locations in the field over an area of 8 acres. The spatial patterns of trees were analyzed using Ripley's *L(d)*. The stand map was projected using a geographic information system with measured tree attributes for visual representation of the stand in the spatial context. The result indicated that the forest represented a random spatial pattern, but spatial patterns varied by species and size classes. For example, among the dominant species, red maple species represented a random spatial pattern while red oak, chestnut oak and yellow-poplar had clustered spatial patterns. Larger trees(d.b.h. >18 inches) were found to be uniformly dispersed while smaller trees had random patterns. We suggest that shade tolerance of trees can be used as an indicator variable in generalizing random spatial pattern. This generalization could be helpful in planning silvicultural activities in a stand.

INTRODUCTION

Spatial patterns of trees in forests are important elements for understanding ecosystem dynamics (Veblen and others 1979). However, the potential for improved ecological understanding afforded by spatially explicit analysis has not been fully recognized (Franklin and others 2002). The existing spatial structure of the stand may be viewed as resulting from species adaptation to a particular ecological niche as a deterministic process and localized dispersal events as a stochastic process (Hubbell 2001). The mainstream approach to community ecology has been to search for deterministic processes that explain the particular adaptations of each species to abiotic factors, or interactions among species (Hardy and Sonke 2004). The existing tree spatial patterns can be used to infer intra- and interspecific interactions among plants (Pielou 1977, Greg-Smith 1979), and explain certain stand attributes. For example, Leopold and others (1985) explained that the existing random spatial pattern in smaller trees may be the result of shade tolerance, seed production, and available growing space. Based on these insights, we hypothesized that tree characteristics can be used to generalize stand spatial patterns.

Geographic information systems (GIS) provide a framework within which large spatial databases can be stored, retrieved, and manipulated quickly and easily, allowing efficient data analysis and statistical inference techniques (Cressie and Kornak 2002). Location of individual trees can be accurately mapped in GIS and tree records can be identified by addresses in established spatial units. These spatial data can be analyzed in a visual interface and such visual representation of stand spatial pattern can aid in interpreting various spatial statistical tests that can be calculated using most GIS software packages. For example, Ripley's *K* function uses distance between all possible pairs of points by increasing the search radius to detect pattern at multiple scales (Ripley 1977, Moeur 1993).

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In this study, we used GIS to characterize the tree spatial patterns in a mixed hardwood forest stand in West Virginia and explored the possibility of identifying stand characteristics such as d.b.h., height, crown width, and shade tolerance as indicator variables for particular spatial patterns in the stand. The generalized spatial patterns can be helpful in reconstructing stand disturbance history as the existing spatial patterns reflect primarily disturbance history, such as fire (Rebertus and others 1989, Skarpe 1991, Woods 2004), edaphic factors, or weather patterns, e.g. droughts (Couteron and Kokou 1997). Similarly, knowledge of pattern can be used to select efficient and economical harvesting techniques and equipment. For example, drive-to-tree machines used in forest harvesting are less expensive to purchase and operate and are more productive in scattered stands (i.e., for random or regular spatial patterns). Swing-to-tree type machines, which are expensive to purchase and operate, are productive in clustered stands (Green and Reisinger 1999).

STUDY AREAS

The study area was a 75-year-old, second-growth mixed hardwood forest stand located in the 2800-ha West Virginia University Forest. The forest is located approximately at 39.66°N, 79.78° W. The elevation of the field study sites ranged between 2001 ft and 2310 ft. The major species at the forest are northern red oak (*Quercus rubra*), yellow-poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), and chestnut oak (*Q. montana*).

METHODS

Twenty 0.4-acre square plots were laid out to the northwest and southeast of Glade Run Stream. Diameter at breast height (d.b.h.), total height, crown height, crown length, and crown diameter were recorded for all living trees with d.b.h. ≥5.0 in. A subsample of smaller trees (2 - 5 in d.b.h.) was measured in one plot to analyze the spatial patterns of smaller trees.

Each plot was converted to a planar coordinate system by transforming to the northwest corner of each plot as origin (0,0). Plots were randomized in the analysis framework to avoid plot-level bias. Tree locations were measured using a laser hypsometer and digital compass. Precise tree centers were obtained by adding stem radius to the horizontal distance from laser location to tree stem. Tree locations were projected to Universal Transverse Mercator (UTM) upon registering the locations into corresponding geographical units (Snyder 1987) in GIS. The spatial pattern of trees (by species, d.b.h., crown width, and total height) was determined by using the Ripley's *L* function (standardized Ripley's *K* function) (Ripley 1976, 1981, Besag 1977) as in equation (1). Ripley's *L* function computes the overall mean number of points lying within a circular search window of radius d and stabilizes and linearizes the variances and edge corrections:

$$\hat{L}(d) = \sqrt{\left(A\sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N}k_{ij}\right)/\left(\prod(n-1)\right)} \qquad (1)$$

where A is area, N is the number of points, d is the distance and k_{ij} is the weight, which is 1 when the distance between i and j is less than or equal to d and if there is no edge correction, and when the distance between i and j is greater than d. When the edge correction is applied, the weight of k_{ij} is modified slightly.

The expected value of $\hat{L}(d)$ under a Poisson process (i.e., Complete Spatial Randomness or CSR) is 0, positive values indicate clustering, and negative values indicate spatial segregation. We used Monte Carlo simulations of Poisson process to provide a 95 percent confidence envelope (Burrough and McDonnel 1998) by randomly relocating each tree 99 times over the study area. The maximum and minimum simulated *K* values of these random patterns corresponded to the maximum and minimum of the

Table 1.—Stand characteristics by species. Figures represent mean value and figures in parenthesis represent associated standard deviation.

	Trees per acre	DBH (inch)		Height (ft)		Crown height (ft)		Crown width (ft)		Basal area (ft^2/acre)
For all trees larger than 5 inches d.b.h										
American beech	0.1	5.2	(-)	25	0	16	(-)	22	(-)	0.02
Black cherry	9	12.8	-4.1	65.8	-17.7	50.4	-16.9	25.3	-11.3	8.06
Black gum	2.3	6.4	-1.1	29.6	-8.9	20.1	-8	13.9	-4.5	0.5
Black oak	1.4	12.3	-2.8	72	-6.9	53.5	-13.8	28.4	-11.3	1.14
Blue beech	0.6	11.3	-3.5	59.4	-8.8	46.8	-8.9	26.6	-5.5	0.44
Chestnut oak	14.4	11.3	-3.4	65.1	-16.8	51	-15.8	23.4	-9.7	9.96
Cucumber tree	4	11.1	-3.3	61.8	-18.1	49.5	-18.8	19.4	-7	2.7
Elm	0.1	5.8	(-)	36	0	18	(-)	22	(-)	0.02
Hickory	0.9	12.3	-3.9	61.1	-18.2	41.3	-14.8	27.6	-14.5	0.72
Red maple	42.3	8.3	-3	43	-15.3	30.5	-13.6	20.2	-6.8	15.72
Red oak	24.8	15.2	-5.2	72.5	-14.5	54.8	-15.3	32.7	-11.9	31.2
Sassafras	4.8	12.1	-3.2	54.7	-15.1	39.7	-10.6	17.8	-6.9	3.78
Sourwood	3.4	14.6	-4.9	71.3	-16.8	54.4	-18.3	35.5	-12.7	3.92
Sweet birch	0.3	5.6	-0.3	23.5	-1.5	17	-1.4	18.5	-0.7	0.04
White ash	0.3	19.7	-7.1	83.5	-0.5	70	0	41	-7.1	0.53
White oak	6.6	13.8	-5.1	68.7	-15.1	53.3	-15.2	28.3	-13.5	6.84
Yellow-poplar	22	16.7	-4.7	79	-15	64.4	-13.8	31.4	-11.1	33.61
Total	137	12.2	-5.2	61.1	-21.1	46.6	-19.5	25.7	-11.3	110.99
For trees in 2 – 5 inches d.b.h. (from one sample plot)										
Black cherry	0.6	2.9	-1	20.6	-5.1					0.2
Black gum	0.1	2.5	(-)	18.6	(-)					0
Red maple	1	4.1	-0.6	36.3	-8.7					0.7
Total	1.8	3.6	-0.9	29.4	-10.8					1

confidence envelope at each d. If observed *L(d)* values are inside the confidence envelope, the observed spatial distribution is likely to be random. If values are larger than the upper confidence envelope, then distribution is significantly clustered and if less, significantly uniform.

RESULTS

Stand Description

Stand density was 137 trees per acre with four species comprising more than 75 percent of total tree density: red maple (RM), northern red oak (RO), chestnut oak (CO), and yellow-poplar (YP). Total basal area was 111 square feet per acre (Table 1). Average stand d.b.h. was 12.2 in., average height was 61.54 ft, average crown height was 46.60 ft, and average crown width was 25.7 ft.

The smaller diameter classes were composed mainly of red maple; yellow-poplar and northern red oak made up the majority of trees in larger diameter classes (Fig. 1). Of the four major species, red maple was found in the understory, and its height distribution was shortest. Yellow-poplar and northern red oak dominated the canopy of the stand (Fig. 2). Among the four dominant species analyzed, northern red oak and yellow-poplar tended to have wider crowns while red maple and chestnut oak had smaller crowns (Fig. 3).

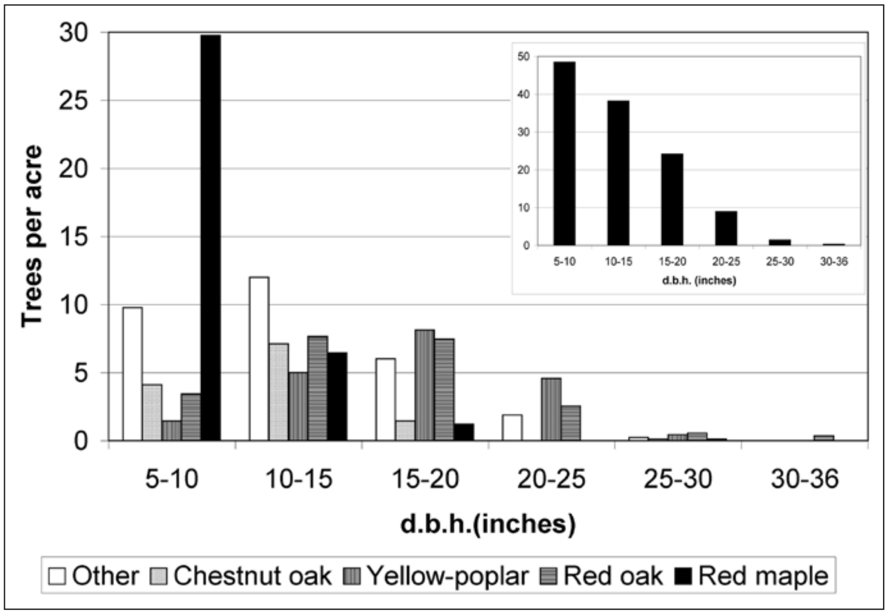

Figure 1.—Stand diameter distribution of four major species and for all species combined (in inset). The estimated stand age is 75 years and it is a mixed hardwood stand.

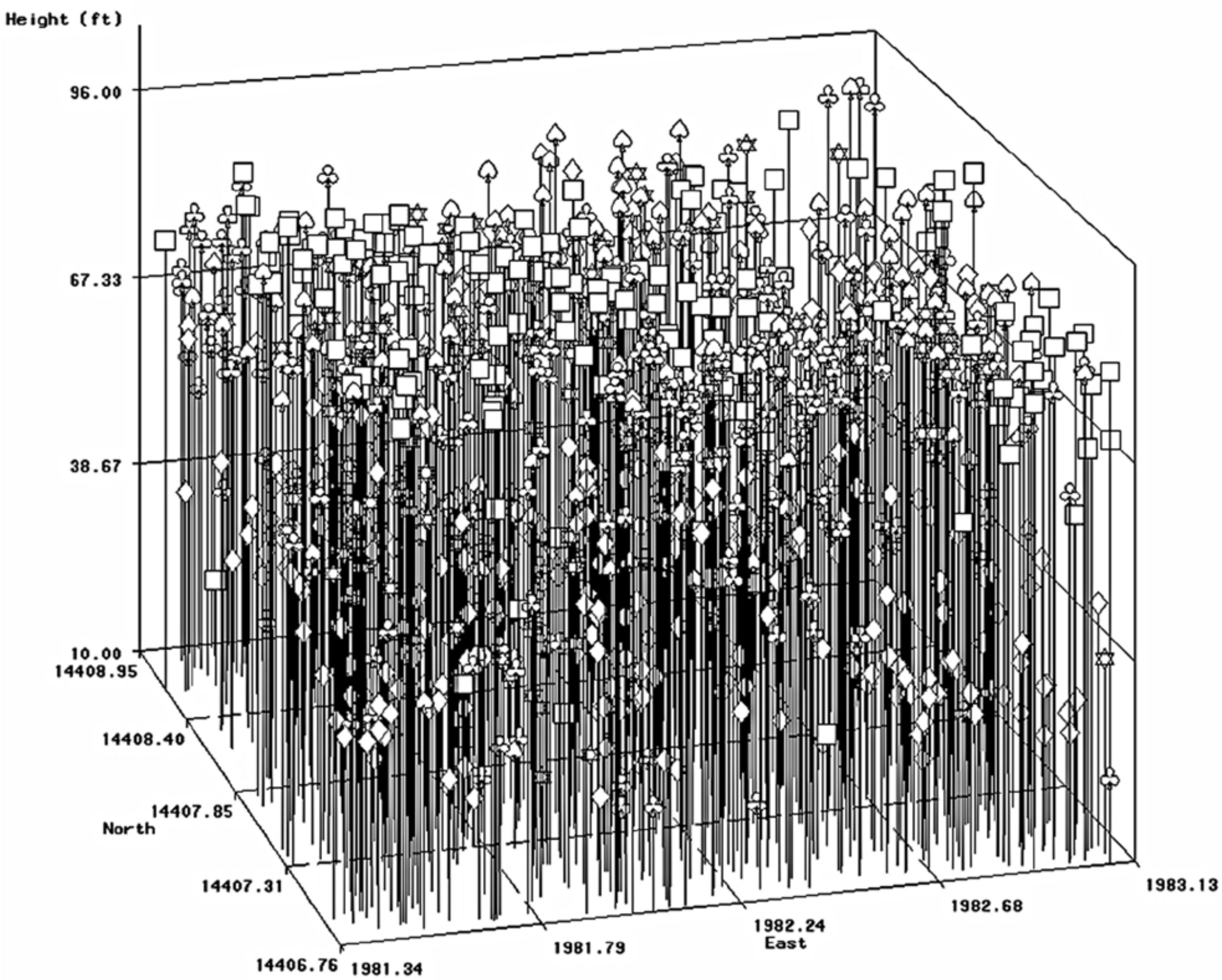

Figure 2.—Height profile of trees in the study area. The North and East coordinate systems (i.e. Y and X) are drawn to Universal Transverse Mercator (UTM) and represent UTM equivalent to ’000 feet distance. The coordinate has a false easting component of 1,640,000 ft. (Legend: spade for red oak, square for yellow poplar, diamond for red maple, star for chestnut oak, and club for all other species).

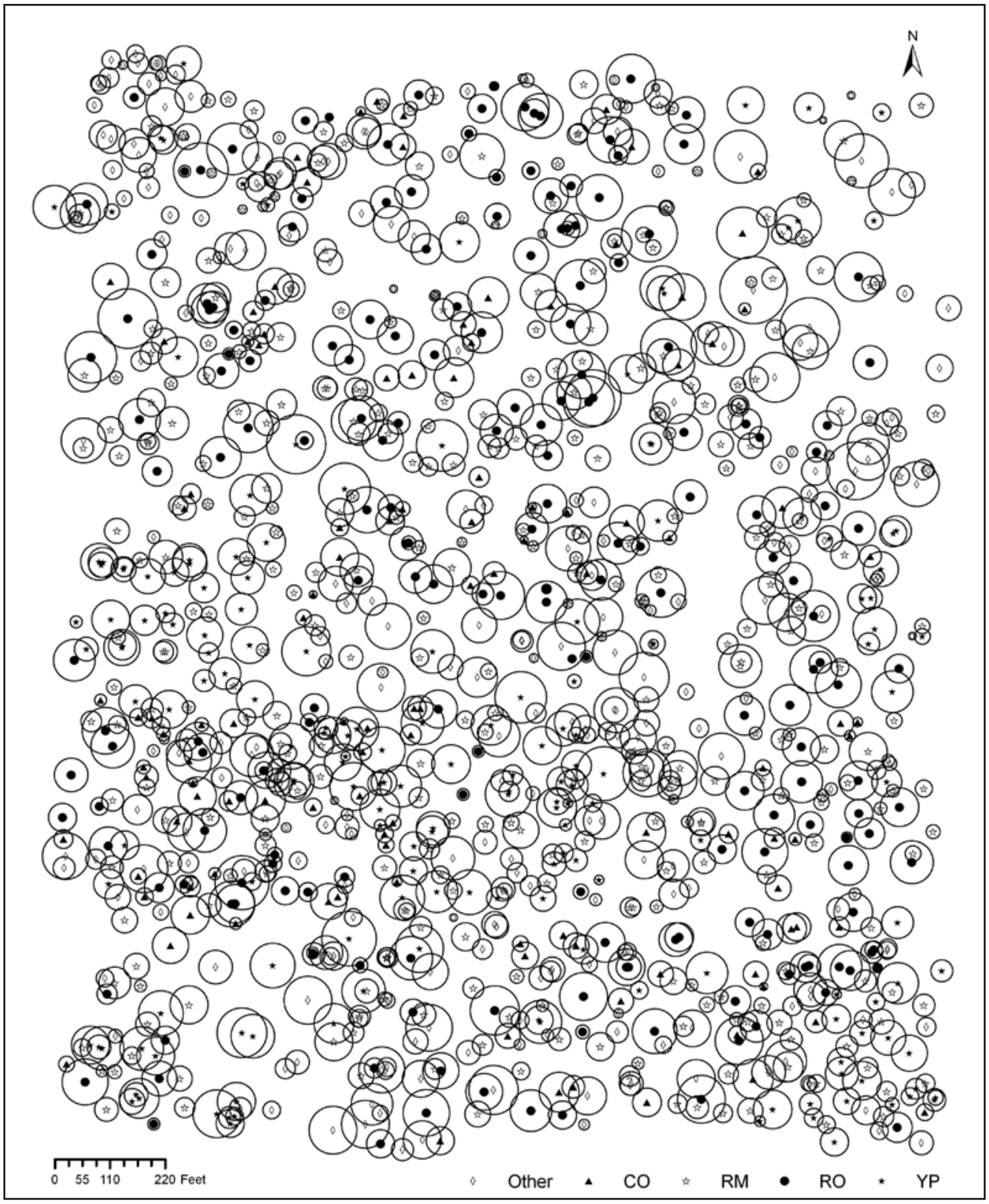

Figure 3.—Spatial distribution of trees with individual tree crown width drawn to scale. The circle diameter represents the crown width. The gaps within the stand are either smaller trees which were not measured during the study or natural gaps in the stand.

Spatial Pattern

L(d) plots indicated that overall the stand's tree distribution was not significantly different from random or CSR (Fig. 4b). However, this pattern was not uniform for all species. Among the four major species, red maple showed a random spatial pattern while northern red oak, chestnut oak, and yellow-poplar each showed a clustered pattern (Fig. 4c-f). The spatial pattern tended to vary by distance (i.e., scale of observation). For example, yellow-poplar tended to become more clustered at a distance of 48 to 112 ft and tended to come closer to random pattern at broader scales (i.e., >160 ft). On the other hand, red oak's distribution pattern was random at finer scales and clustered when distance increased. The spatial pattern analyzed for smaller trees (d.b.h. 2 to 5 in.) in a randomly selected plot showed that the existing pattern was random for all distances (Fig. 4a).

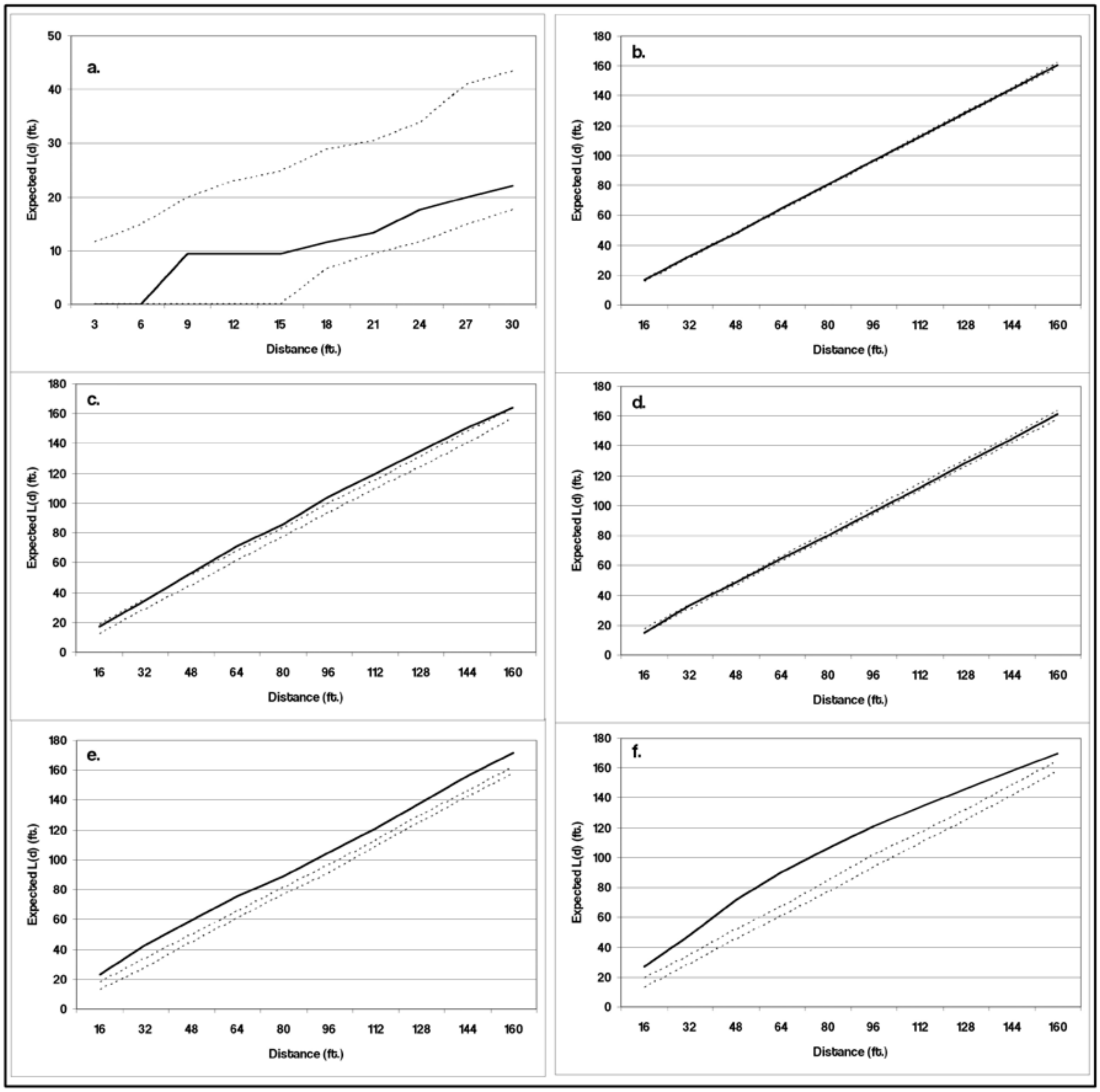

Figure 4.—Spatial pattern as function of L(d) of smaller trees (a.), for all the species (b.) and for major species red oak (c.), red maple (d.), chestnut oak (e.) and yellow poplar (f.). The dotted lines are the 95 percent confidence envelopes for spatial randomness and the solid line is the existing spatial pattern. A solid line above the confidence envelope indicates a significant clustered pattern while a line below the envelope indicates a significant regular (dispersed) pattern.

We also analyzed the spatial pattern of trees based on d.b.h., height, and crown width (Fig. 5). The distribution of larger trees (d.b.h. >18 in.) was regular while smaller trees (d.b.h. <18 in.) were distributed randomly at shorter distances and showed a clustered pattern at larger reference distance. Taller trees had a clustered pattern while shorter trees had a random pattern. Trees with larger crown width (>20 ft) had random distribution at reference distances up to 40 ft and were clustered at higher reference distances. Trees with smaller crowns (<20 ft) had a random spatial pattern.

While conducting species-level analysis of the four major species, we found that only red maple showed a random spatial pattern. A review of silvical characteristics of all the major species showed that red maple differs from other species only in its ability to tolerate shade. Shade-tolerant species including maple were randomly distributed in the stand (Fig. 6).

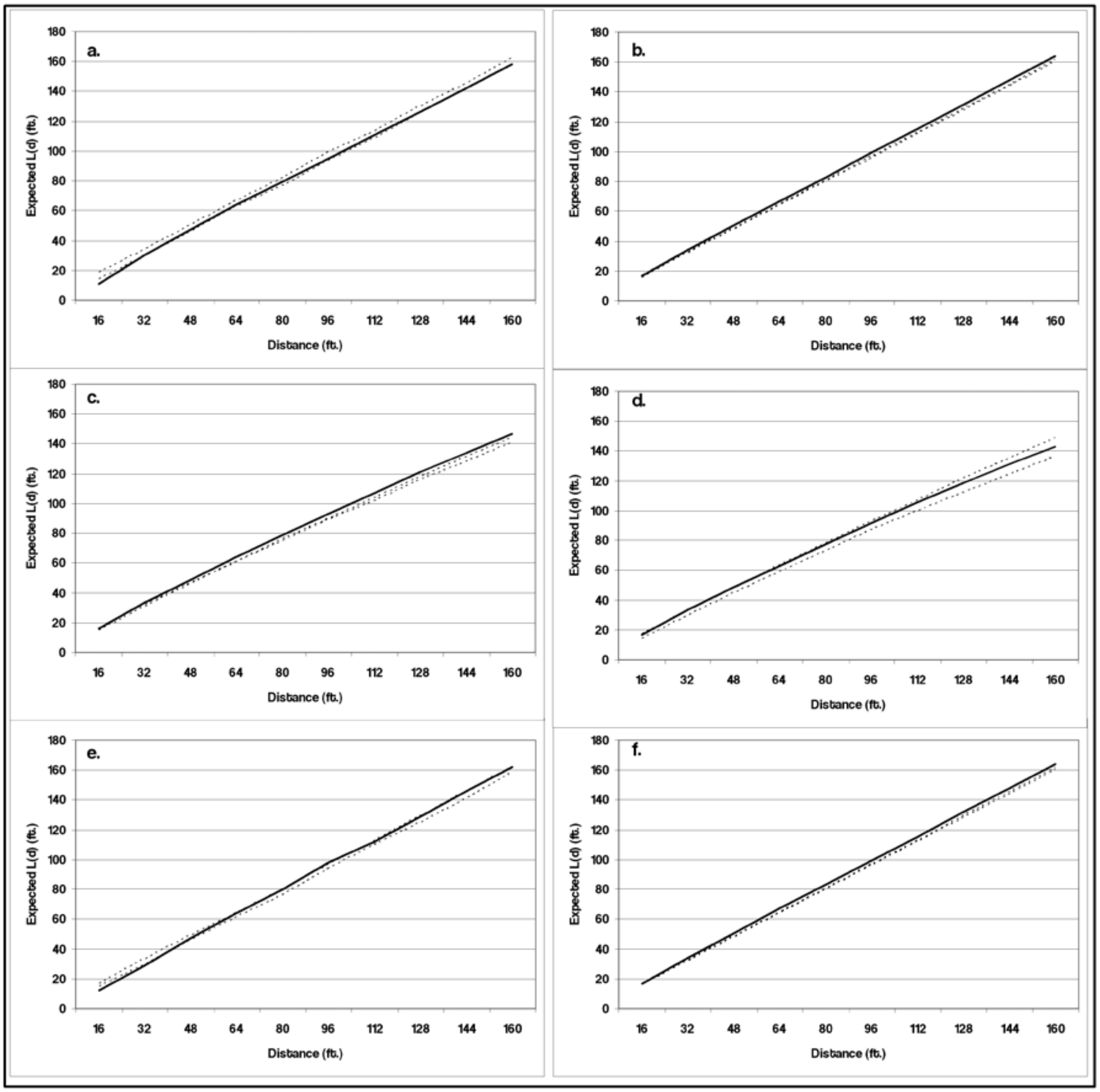

Figure 5.—Spatial pattern as function of *L(d)* by different size attributes (d.b.h., total height, and crown width). Spatial pattern of trees with d.b.h. >18 inches (a.); d.b.h. <18 inches (b.); height >33 ft (c.); height <33 ft. (d.); crown width >20 ft (bottom left) and crown width <20 ft (e.).

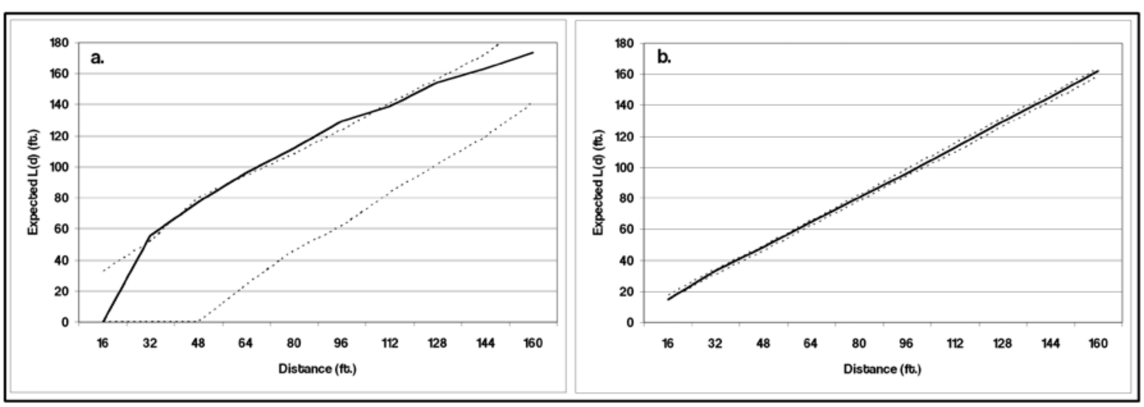

Figure 6.—Tree spatial pattern as function of *L(d)* in shade-tolerant species excluding red maple (a.), and including red maple (b.).

DISCUSSION AND CONCLUSIONS

The stand explored in this study represents a central hardwood stand for West Virginia based on the characteristics described by Hicks (1998). The spatial pattern of trees across the study area was random. This pattern was consistent with studies conducted in similar hardwood regions (e.g., Chokkalingam and White 2001).

In our stand, red maple comprised of about one-third of stem density. This species is considered adapted to a broad spectrum of environmental conditions, and in the central hardwood region, emerges as both pioneer and climax species (Hicks 1998). In our analysis, we found that red maple had a random spatial pattern. The existing pattern of these species can be related to their ecological role and silviculture. For example, red maple's shade tolerance enables it to persist on a range of sites. In our stand, site availability could be a function of tree mortality, which creates canopy gaps. In the absence of anthropogenic disturbance, gap creation often is a spatially random phenomenon and, in younger stands, gap sizes are generally small. Red maple can opportunistically establish in small, randomly distributed gaps and thus approximate a random spatial pattern.

Large trees with wide crowns affect the distribution of smaller trees in the forest understory. Crown-width mapping, together with the height profile, gives insights into the existing stand structure. For example, red maple, which was mostly found in the understory (Fig. 2), also exhibited smaller crowns (Fig. 3) in this stand. The shorter trees, trees with smaller diameters, and those with smaller crown widths growing in the understory were able to persist under shady conditions and had random spatial patterns. The shade-intolerant species—northern red oak, chestnut oak, and yellow-poplar—exhibited clustered spatial patterns.

Although several processes are involved in stand spatial pattern including past disturbances, life history strategy, ecological role, species regeneration guilds, differential resource use, dispersal and germination mechanisms or reproductive strategies (Agren and Fagerstrom 1984, Bazzaz 1990, Sutherland and others 2000), it is possible that trees growing in shade are affected by those processes and can be used as an indicator variable to generalize the existing spatial pattern in the stand as a quick assessment of random spatial distribution in the stand. Although our analysis was able to detect the linkage between shade tolerance and random spatial distribution, it could be possible that this was a result of a random chance event. Future research with different datasets from comparable stands could give further insights into predicting spatial pattern and validate this research. Similarly, the spatial pattern analysis conducted in different size classes can be extended to temporal measurements to understand the spatial pattern of forest turnover. Once we obtain acceptable predictive ability based on indicator variables like shade tolerance in regards to spatial pattern, stand simulation using a desktop system may be more accurate for silvicultural prescriptions and harvest scheduling.

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USING LIDAR AND COLOR INFRARED IMAGERY TO SUCCESSFULLY MEASURE STAND CHARACTERISTICS ON THE WILLIAM B. BANKHEAD NATIONAL FOREST, ALABAMA

Jeffrey Stephens, Luben Dimov, Callie Schweitzer, and Wubishet Tadesse[1]

Abstract.—Light detection and ranging (Lidar) and color infrared imagery (CIR) were used to quantify forest structure and to distinguish deciduous from coniferous trees for selected stands on the William B. Bankhead National Forest in Alabama. Lidar bare ground and vegetation point clouds were used to determine tree heights and tree locations. Lidar accuracy was assessed by comparing Lidar-derived tree heights to field-measured tree heights. An independent t-test showed Lidar-derived coniferous tree heights were statistically the same as field-measured heights ($p = 0.24$). Likewise, the mean Lidar deciduous tree heights were statistically the same as the average field-measured tree heights ($p = 0.10$). The CIR photograph analysis detected groves of coniferous and deciduous trees. The overall classification accuracy of deciduous and coniferous vegetation in the CIR image was 95.59 percent. Our research demonstrates the ability of Lidar to correctly determine tree height and tree location in a mixed pine-hardwood forest. The results obtained from this study indicate that Lidar can assist ecologists and managers to make decisions that would be difficult to make if based solely on field measurements.

INTRODUCTION

Light detection and ranging (Lidar) is used to describe at an unprecedented level of detail the biophysical characteristics of woody vegetative communities. Recently, Lidar has proven to be of great assistance to ecologists and foresters by efficiently determining tree heights and other forest attributes (Lefsky and others 2002, Brandtberg and others 2003, Evans and others 2006). The use of Lidar systems in forestry has come about in part because of the need for faster, less expensive, and more accurate forest data collection (Blair and others 1999, Evans and others 2006, Koukoulas and Blackburn 2004). Lidar has the capability to provide forest measurements at fast rates, low costs, and high accuracies that cannot be obtained through field measurements (Anderson and others 2006a). In particular, Lidar can characterize forest ecosystems in more detail than typical remote sensing applications by determining stand structure, composition (when combined with other remote sensing methods), tree height, crown dimensions, leaf area index, basal area, and aboveground biomass (Lefsky and others 2002, Naesset and others 2004, Popescu and others 2003). Moreover, the ability of Lidar to remotely measure tree height and crown size for great expanses of forest is useful to further understand ecosystem structure and function (Blair and others 1999).

Specific research objectives of this study were to (1) test if Lidar can measure individual tree heights in the forest types of the William B. Bankhead National Forest (BNF) in Alabama; and (2) examine the capabilities of Lidar data in combination with infrared imagery to distinguish pines from hardwoods and identify tree locations for a mixed pine-hardwood stand in the BNF. We tested the difference between Lidar and ground-measured tree heights for both deciduous and coniferous trees in a forest on the mid-

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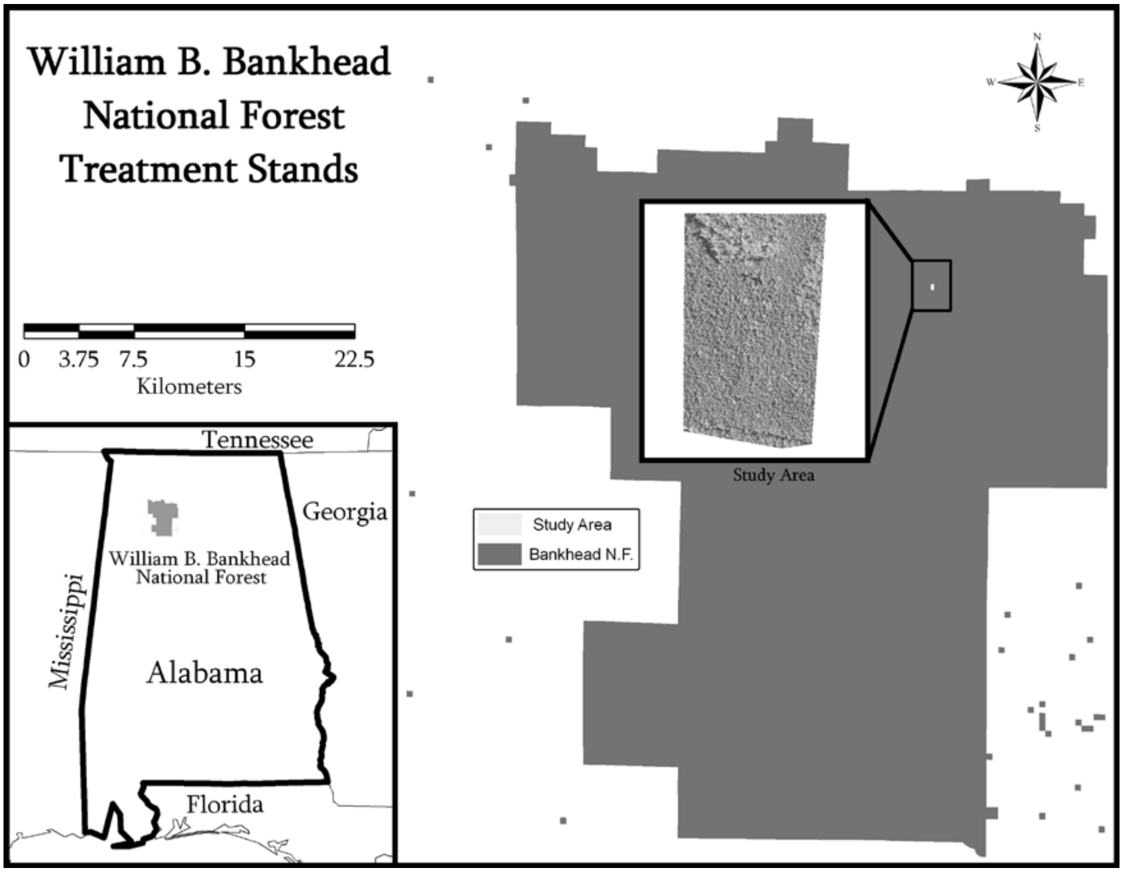

Figure 1.—The study area located in the BNF.

Cumberland Plateau that was not previously sampled with Lidar. Hudak and others (2002), Popescu and others (2004), and Anderson and others (2006b) have shown that Lidar can be used to measure tree height, location, and crown size in different forest types.

STUDY AREA

The study area (Fig. 1) is located on the northern third of the BNF in Lawrence County, AL. The BNF is within the Cumberland Plateau region of the southern Appalachian Mountains described as having gentle slopes and broad undulating uplands (Smalley 1982). The soils of this subregion are moderately deep, well drained, and permeable (fine-loamy, siliceous, semiactive, thermic Typic Hapludults). The stands are dominated by even-aged loblolly pine (*Pinus taeda* L.) with some Virginia pine (*P. virginiana* L.) volunteers, but management objectives are aimed at shifting the stands towards an upland hardwood dominated composition.

MATERIALS AND METHODS

Data

Lidar data were collected for selected BNF stands on July 2, 2005 with an Optech Airborne Laser Terrain Mapper 3100 instrument. This Lidar multi-return system, two returns, uses a scanning laser to measure the earth and vegetation below the aircraft by recording the start of the laser pulse and the return time of the laser to the system sensor. Because the flight elevation and exact location of the plane are recorded with a Real-Time Kinematic Global Positioning System and an Inertial Measurement Unit for each laser return, we can calculate the ground topography and the height of the vegetation by knowing the speed of light, angle of pulse, and the x, y, and z orientation of the airplane. The Lidar was acquired at an altitude of 910

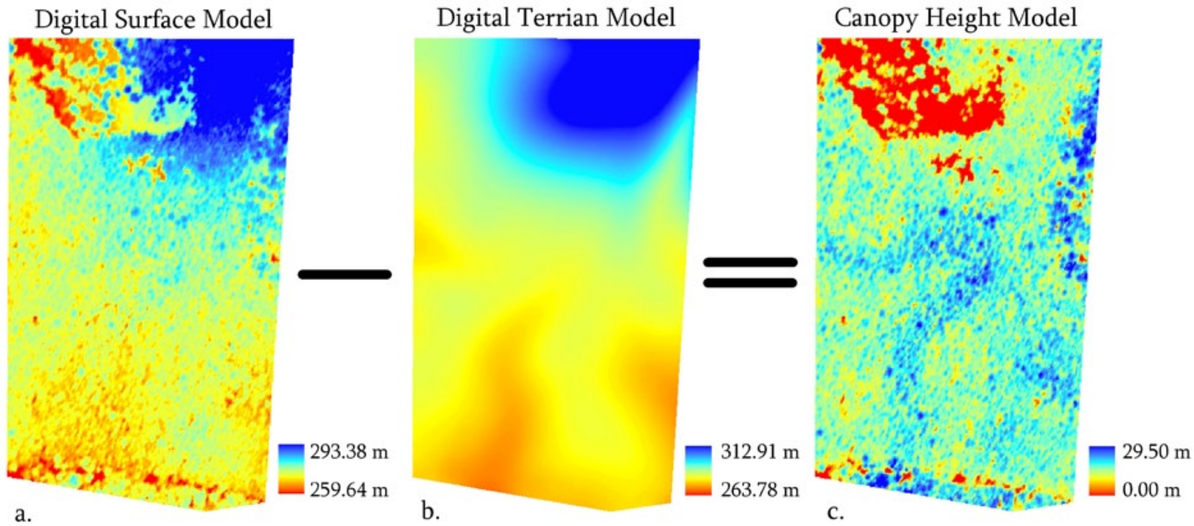

Figure 2.—Process to obtain the vegetation heights. The digital terrain model (b) was subtracted from the digital surface model (a) to produce the canopy height model (c).

m to achieve a footprint of 0.27 m with a point density of three postings per square meter. In addition to Lidar, digital CIR photographs were collected for the entire BNF on September 9, 2005. The CIR photographs were obtained at an altitude of 3290 m such that a photo scale of 1:21,600 was achieved with a spatial resolution of 0.50 m.

Interpolation

To determine tree heights and locations, it was necessary to classify the Lidar points into two different categories. The result of classifying the Lidar data were two sorted point clouds: bare earth returns, which represented the ground topography because the points were reflected by the ground, and first return, which depicted vegetation heights because they were reflected by vegetation. Once the vegetation and the bare earth point clouds were sorted based on elevation above an ellipsoid, both point clouds were used to create the interpolated terrain models (raster images) that allowed us to calculate tree heights.

The terrain models were interpolated using three different methods: Inverse Distance Weighted (IDW), Universal Kriging (UK), and Ordinary Kriging (OK). We tested the best interpolation method based on the amount of error between the predicted and the measured points for IDW, UK, and OK. A digital terrain model (DTM) was created from the bare earth and first returns such that each 0.5 m pixel represented the ground elevation. A digital surface model (DSM) was then developed to represent the above ground vegetation with a 0.5 m spatial resolution. Both the DSM and DTM images were interpolated using the OK method. The canopy height model (CHM) was produced by subtracting the DTM image from the DSM image to obtain the vegetation heights for the study area (Fig. 2). The resulting CHM raster image contained the vegetation heights that were used to obtain tree locations, heights, and crown dimensions in TreeVaW. TreeVaW© is a software application used to extract forest inventory parameters from Lidar data. The tree heights calculated in TreeVaW were compared to the field height measurements.

CIR Classification

The CIR study area image was classified by iteratively selecting representative groupings of deciduous and coniferous trees based on spectral differences. The deciduous class was dominated by the *Quercus* species and the coniferous class was dominated by loblolly pine and Virginia pine. Supervised classification produced an image that identified the locations of deciduous and coniferous trees. The accuracy assessment of the CIR image calculated a consumer's accuracy, or the chance of correctly determining what is actually on the ground; producer's accuracy, the probability the map is correctly classified; commission error, the chance of including a pixel in a class when it should have been excluded; and omission error, the probability of excluding a pixel that should have been included in the class. The high overall accuracy obtained from the CIR image allowed us to separate the coniferous trees from the deciduous trees, so TreeVaW's tree height algorithm could model each category separately. The CIR image and the Lidar data were georeferenced using a Real-Time Kinematic Global Positioning System prior to analysis so both data sets were co-registered.

Tree Measurements

Field data were collected by using a ForestPro laser range finder (Laser Technology, Inc., Centennial, CO) to obtain 75 tree heights. The trees whose heights were collected were selected by establishing five plots in a systematic manner and measuring the 15 trees in each plot that were closest to plot center and had diameter at breast height (d.b.h.) over 1.5 inches. Among the measured trees were both overstory and midstory trees that would not be clearly visible in the Lidar. We excluded from the analysis by taking the average of the field-measured trees and omitting those that were less than an arbitrarily assigned height of 75 percent below the mean. The field-measured tree heights were considered to be the correct measurement, thus allowing the accuracy of the Lidar-derived tree heights to be assessed. We compared the field-measured tree height averages to the average Lidar derived tree heights using an independent t-test at an alpha level of 0.05 in SPSS ver. 11(SPSS Inc., Chicago, IL). We did not compare individual field-measured trees with individual measured trees located with the Lidar data.

TreeVaW was used to identify tree location and tree height. The TreeVaw algorithm is based on the local maximum filtering technique that uses a search window of variable size (Kini and Popescu 2002). The local maximum technique is typically used in multispectral imagery to find the greatest reflection point to denote the apex. In this study, however, the local maximum was used with the Lidar CHM data because the vegetation heights in the CHM are analogous to reflection pixels.

The TreeVaw algorithm reads the height value from each pixel in the CHM and calculates a window size to search for the local maximum. The variable window that is used to represent tree canopy can be either a circle or a square. The algorithm filters the image within a window shape and identifies the local maximum. After the location of each identified tree has been marked, the CHM is sampled at the local maximum to determine the height of each tree. TreeVaW avoids low vegetation by setting a minimum tree height to be used. For this study the minimum tree height was set to 3.00 m.

Two separate TreeVaw processes were run to identify coniferous and deciduous trees. The coniferous trees were set to a smaller crown width size (3.00-5.00 m) that was determined by measuring the crown width in the classified coniferous CIR image. For the deciduous trees we used a larger crown width (7.50-10.00 m) that was also determined by measuring the crowns in the area classified as deciduous.

The data were processed with ArcGIS (9.2) software (Environmental Systems Research Institute, Inc., Redlands, CA), ENVI (ITT Visual Information Solutions, Boulder, CO) remote sensing software, and Tree Variable Window (TreeVaw), an ENVI application (Kini and Popescu 2004).

Table 1.—Accuracy assessment for the classified CIR image. Note that the percentage correct equals the sum of the diagonal divided by the total observations (e.g., 1737/1817 = 95.5 percent)

Classified data	Deciduous pixels	Coniferous pixels	Row total	Producer's accuracy	Omission error
Deciduous pixels	1230	17	1247	98.60%	1.40%
Coniferous pixels	63	507	570	88.90%	11.10%
Column total	1293	524	1817		
Consumer's accuracy	95.10%	96.70%			
Commission error	4.90%	3.30%			

RESULTS AND DISCUSION

Interpolation

IDW had the highest measure of predicted error and a root-mean-square of 0.24 m. IDW is a simple interpolation method that does not allow a standardized error, such as kriging, to be computed. IDW interpolation produced a generalized image for the bare ground and the predicted error was comparable to UK. The UK method had a predicted error of 0.00 (if using only two significant digits) and root-mean-square standardized error of 1.25 m. UK produced an image that was similar in error to the IDW image, but the IDW and UK results were not as close to the actual values when compared to the OK results. OK had a mean closest to zero and a root-mean-square standardized value of 0.98 m, meaning that the predicted values were close to the actual values. The OK image was selected to calculate the bare earth because the predicted error was near zero and the standardized error value was closest to 1. The vegetation returns were interpolated with OK because of the low error values for the predicted locations.

Tree Heights

The accuracy assessment of the CIR image is summarized in Table 1. The overall accuracy of the CIR image was 95.59 percent with a Kappa statistic of 89.55 percent. The resulting classified CIR photograph shows the location of the deciduous and coniferous trees in the study area (Fig. 3).

TreeVaw identified 739 deciduous trees with an average tree height of 17.78 m and a standard deviation of 2.96 m. The tallest deciduous tree generated from TreeVaw was 29.50 m and the shortest was 12.03 m. The coniferous tree results from TreeVaW were based on 2875 trees with a mean height of 17.99 m and a standard deviation of 2.29 m. The tallest coniferous tree detected with TreeVaw was 28.80 m and the shortest was 12.02 m.

Twenty-five deciduous trees and 38 coniferous trees were measured in the field. The average field measured deciduous tree height was 13.74 m (standard deviation 3.86 m) and the average coniferous tree height was 18.43 m (standard deviation 2.72 m). A t-test for difference in means revealed that the deciduous TreeVaw derived heights were statistically the same as the field-measured deciduous tree heights.

A t-test for difference in means between the coniferous field-measured tree heights and the TreeVaw tree heights showed that they were not significantly different. These results are in accordance with other studies (Popescu and others 2003, Koukoulas and Blackburn 2005, Brandtberg 2007) that have found no major difference between field-measured deciduous tree heights and the Lidar-derived deciduous tree heights. The results indicate that it is possible to accurately measure codominant and dominant tree heights using Lidar data in mixed pine-hardwood southeastern forests of the type in this study.

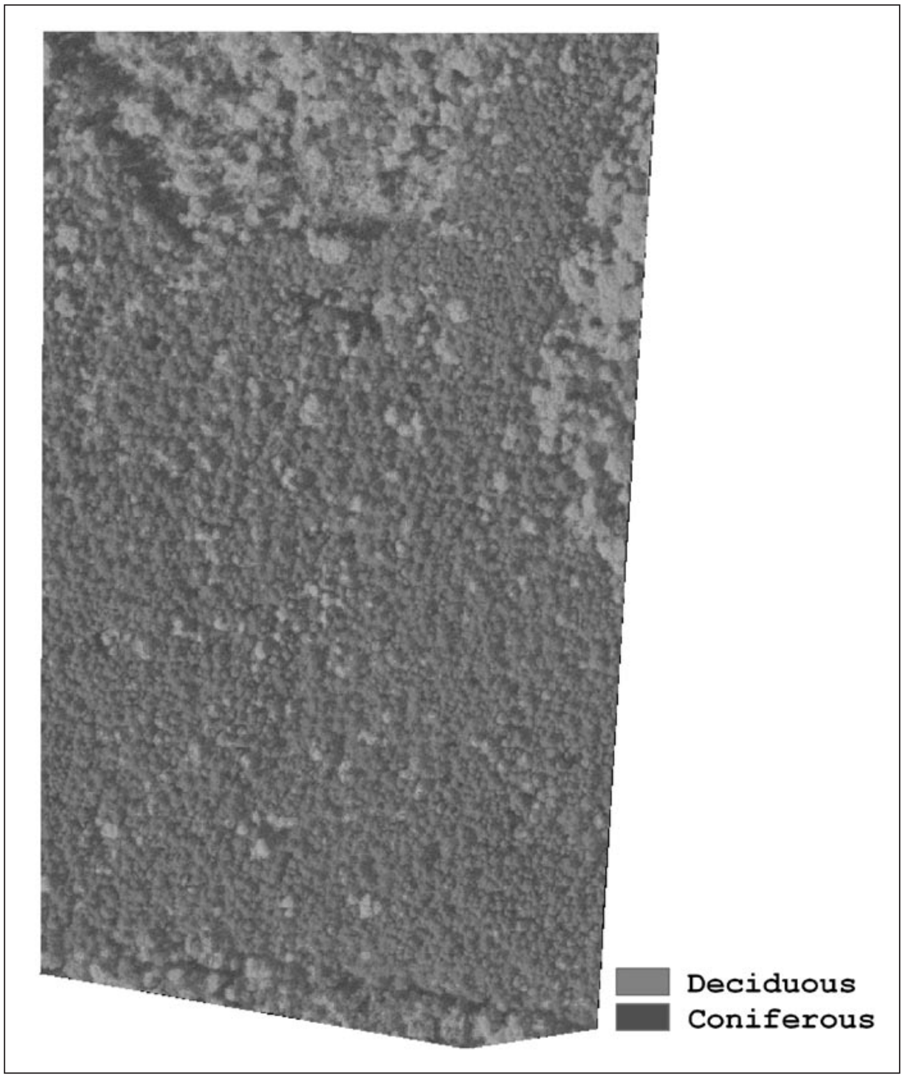

Figure 3.—Classified color infrared image into deciduous and coniferous categories.

CONCLUSIONS

The classification of the CIR photograph was accurate and improved the accuracy of the TreeVaw algorithm. This improvement was accomplished by using two different CHMs for the coniferous and deciduous trees in TreeVaw. This greatly reduced the erroneous number of trees detected using TreeVaw's local maximum filtering technique. The results of the TreeVaw output used in association with field data can assess the accuracy of Lidar derived tree heights. Our results indicate TreeVaw heights are statistically the same as field measured coniferous and deciduous tree heights. The information derived from Treevaw may be used to extract further information from forest stands such as biomass, leaf area index, d.b.h., and basal area.

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ECOLOGICAL MODELING FOR FOREST MANAGEMENT IN THE SHAWNEE NATIONAL FOREST

Richard G. Thurau, J.F. Fralish, S. Hupe, B. Fitch, and A.D. Carver[1]

Abstract.—Land managers of the Shawnee National Forest in southern Illinois are challenged to meet the needs of a diverse populace of stakeholders. By classifying National Forest holdings into management units, U.S. Forest Service personnel can spatially allocate resources and services to meet local management objectives. Ecological Classification Systems predict ecological site conditions based on biotic and/or abiotic factors. Ecological Land Types were identified and mapped for the Illinois Ozark Hills subsection in a geographic information system to provide land managers with a tool for incorporating ecological characteristics into decisionmaking processes. Results are presented as mapping units and written descriptions that describe ecological characteristics based on physiographic land forms and soil characteristics.

INTRODUCTION

The Shawnee National Forest in southern Illinois is a continuously morphing patchwork of forested parcels that are managed by agents of the United States Department of Agriculture Forest Service (USFS) to meet the needs and demands of a diverse range of stakeholders. Currently, the Shawnee contains more than 284,000 acres of National Forest System lands (Shawnee ROD 2006), mostly forested, retired agricultural, or other natural cover. By classifying National Forest holdings into management units, while defining local ecological conditions, USFS personnel can spatially allocate resources and services to meet diverse management objectives. Ecological Classification Systems (ECS) model biotic ecological site conditions based on abiotic characteristics and other factors. ECS provide managers with site-specific ecological information that can be incorporated into decisionmaking processes that must account for opinions from a variety of stakeholder preferences.

Science and Management

Natural resource managers are continually challenged to construct management plans that account for ecological, social, and economic considerations that must incorporate a full spectrum of stakeholder interests. Making effective management decisions requires access to quality information. When employed effectively, geographic information systems (GIS) can be utilized to provide spatial information that is beneficial for understanding many issues important for land management. The development of process modeling in GIS has given managers tools that can generate a range of quality spatially dependent information from present data sources. Automated process models delivered to management personnel will allow spatial information to be updated as new datasets become available.

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Since the late 1970s, the USFS has adopted a strategy of classifying public lands at multiple scales, with divisions based on ecological considerations (ECOMAP 1993). The National Hierarchical Framework of Ecological Units (NHFEU) outlines protocols for delineating continental, regional, and local spatial units that describe relative ecological conditions. This paper will focus on two specific levels of the NHFEU: seven subsections have been delineated within the Shawnee National Forest, representing seven semi-distinct ecological units. The subsection units are typically mapped at a scale of 1:500,000. Within each subsection, six Ecological Land Types (ELTs) were derived using an automated model within a GIS, based on physiographic land forms and soil development characteristics. ELTs are typically mapped at a scale of around 1:24,000. This analysis will examine the six derived ELTs within one subsection (the Illinois Ozark Hills) in the Shawnee National Forest.

As charged by the National Forest Management Act of 1976, public lands managers are required to account for ecological processes when establishing and implementing management practices. Ecological classification systems define geographic units with ecological properties that can be considered during local management decision processes. Ecological classifications linking local biotic and abiotic characteristics have been developed for many ecosystems around the world. Ecological classification systems have been categorized as climatic, vegetative, physiographic, or ecosystematic (Kimmins 1996).

Climatic ecological classifications (e.g., Bailey 1980) usually provide general ecological information over large geographic areas. Climatic classification units may be hundreds of square miles across, lacking the spatial detail needed to make land management decisions. Vegetative classification systems are based on the assumption that the current vegetation is an all-telling indicator of the local ecological conditions. Vegetative classification systems are advantageous in their straight forward assumptions and ability to generate site-level information, but may misclassify areas where disturbance and/or natural succession have altered vegetative species composition.

Physiographic ecological classification systems utilize landform geometry and geography as well as available soils information to determine ecological structure, composition, and productivity. Most physiographic classifications attempt to model moisture availability as the driver of ecological composition. Physiographic ecologic classification models have been developed for many forests in the central hardwoods region, including the Hoosier National Forest, Indiana (Shao and others 2004), the Natchez Trace State Forest, Tennessee (Kupfer and Franklin 2000) and an earlier model in the Shawnee National Forest, Illinois (Fralish and others 2002).

Finally, the ecosystematic approach to ecological classification utilizes recent developments in understanding the complexities of ecological relationships and the technology (such as GIS) that permits the overlay of multiple inputs to define local ecological characteristics.

PROJECT OBJECTIVES

The primary objective of research described here was to adhere to ecological classification system ideals outlined in the ECOMAP (1993) by mapping ELTs to provide forest managers with spatially explicit ecological information that would aid in making informed decisions at a scale useful for management operations. Our approach in this paper describes how and why six ELTs were modeled and mapped in the Illinois Ozark Hills subsection of the Shawnee National Forest. This objective is achieved through the introduction and description of an automated ELT model, developed within a GIS.

Specific objectives of this paper are to:

1. Introduce ecological and computer methods used to model ELTs.
2. Provide descriptive statistics about the geometric and geographic characteristics pertaining to each of six ELTs in the Ozark Hills subsection.
3. Provide maps illustrating exact spatial locations and physiographic characteristics of ELTs in the Ozark Hills subsection.

Links between abiotic (soil and topographic) conditions and biologic (stand) composition in the forests of southern Illinois have been explicitly documented by decades of site-level research (Fralish 1976, Fralish 1987, Fralish 1994, Fralish and others 2002). By using GIS models, we identify site conditions on the landscape providing ecological information for the entire forest. Descriptive information about each ELT will provide managers with a sense of the physiographic conditions that characterize respective ecological units. Illustrated ELT maps overlaid with United States Geological Survey Quadrangle maps ("topo" maps) are an essential part of understanding the spatial complexity of ELTs over a large geographic area such as a subsection. Large-scale (highly detailed) ELT coverage provides spatially explicit ecological information useful for management purposes.

STUDY AREA

Illinois' only National Forest, Shawnee National Forest spans more than 85 miles across 10 counties between the Mississippi and Ohio Rivers (Fig. 1). The approximately 2.4 million people living within 100 miles (160 km) of the forest greatly influence management planning, which must accommodate for many uses, from backcountry camping in seven federally designated wilderness areas, to direct resource use such as timber harvesting.

Ecologically, the forest is located at the western edge of the western mesophytic hardwood forest region (Braun 1965) and is designated as part of the Ozark Plateau Ecoregion by Bailey (1980). The Shawnee National Forest contains seven distinct subsections (Fig. 2) varying greatly by soil depth, soil parent material, soil drainage, and topography.

METHODS

This section describes methods used to derive, map, and spatially characterize six ELTs in the Illinois Ozark Hills subsection. Factors used to delineate ELTs on the landscape were based on decades of empirical research conducted in southern Illinois. Environmental factors were then digitally modeled and mapped as landscape features using GIS. Finally, basic descriptive statistics were determined to geographically and geometrically characterize the six ELTs in the Illinois Ozark Hills.

Identifying Ecological Land Types

Ecological land type criteria were based on over 30 years of forest experimentation in the southern Illinois region (Fralish 1976, 1987, 1994, Fralish and others 2002). Work by Fralish in several locations within the Shawnee National Forest provided empirical evidence indicating a strong relationship between forest types and site conditions. Soil depth, percent slope, hill slope aspect, and alluvial soils were found to be correlated with available soil moisture, in turn driving biologic conditions and the species-site relationships in the region (Fralish 1978).

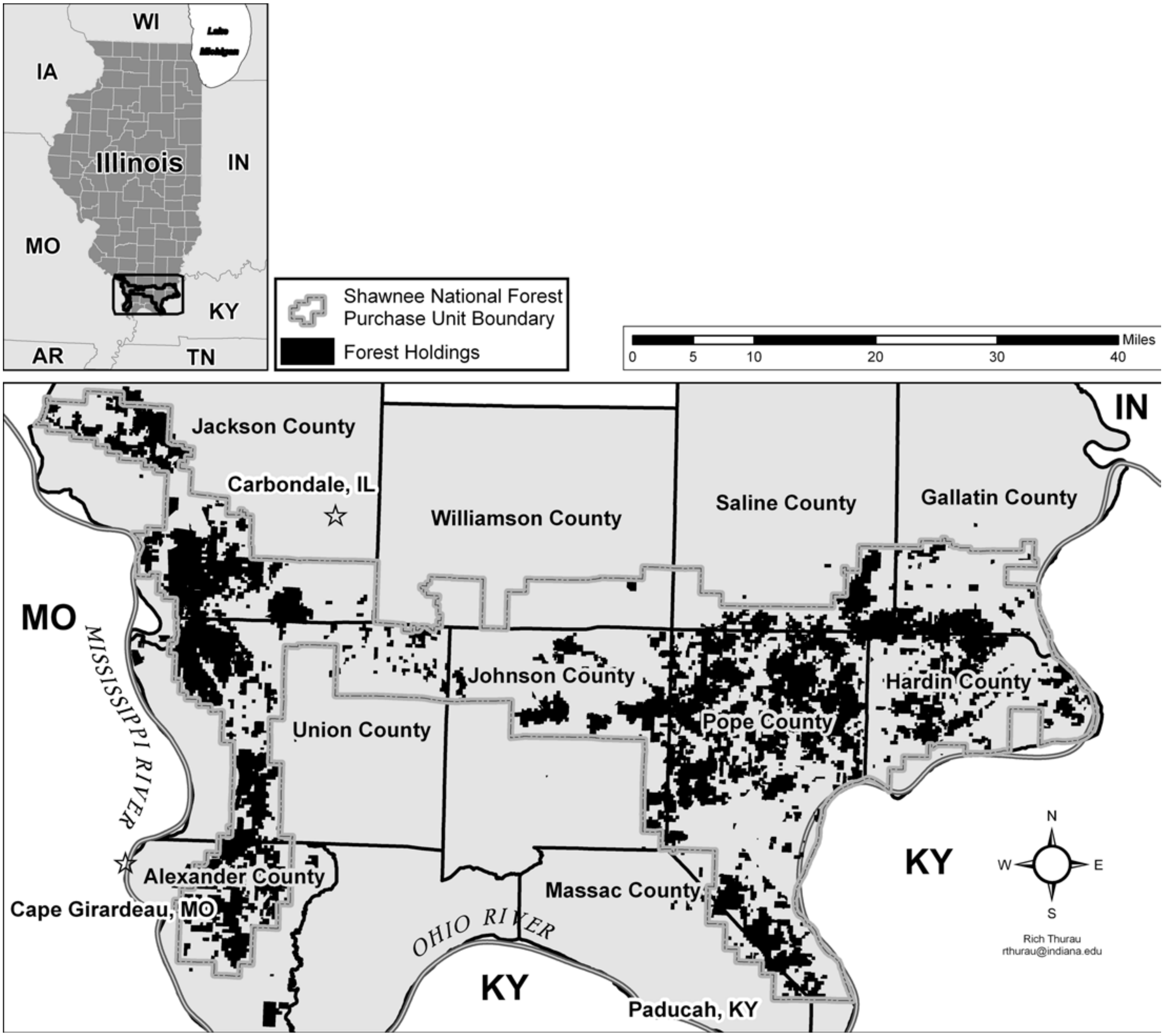


Figure 1.—The study area is the Shawnee National Forest in southern Illinois.

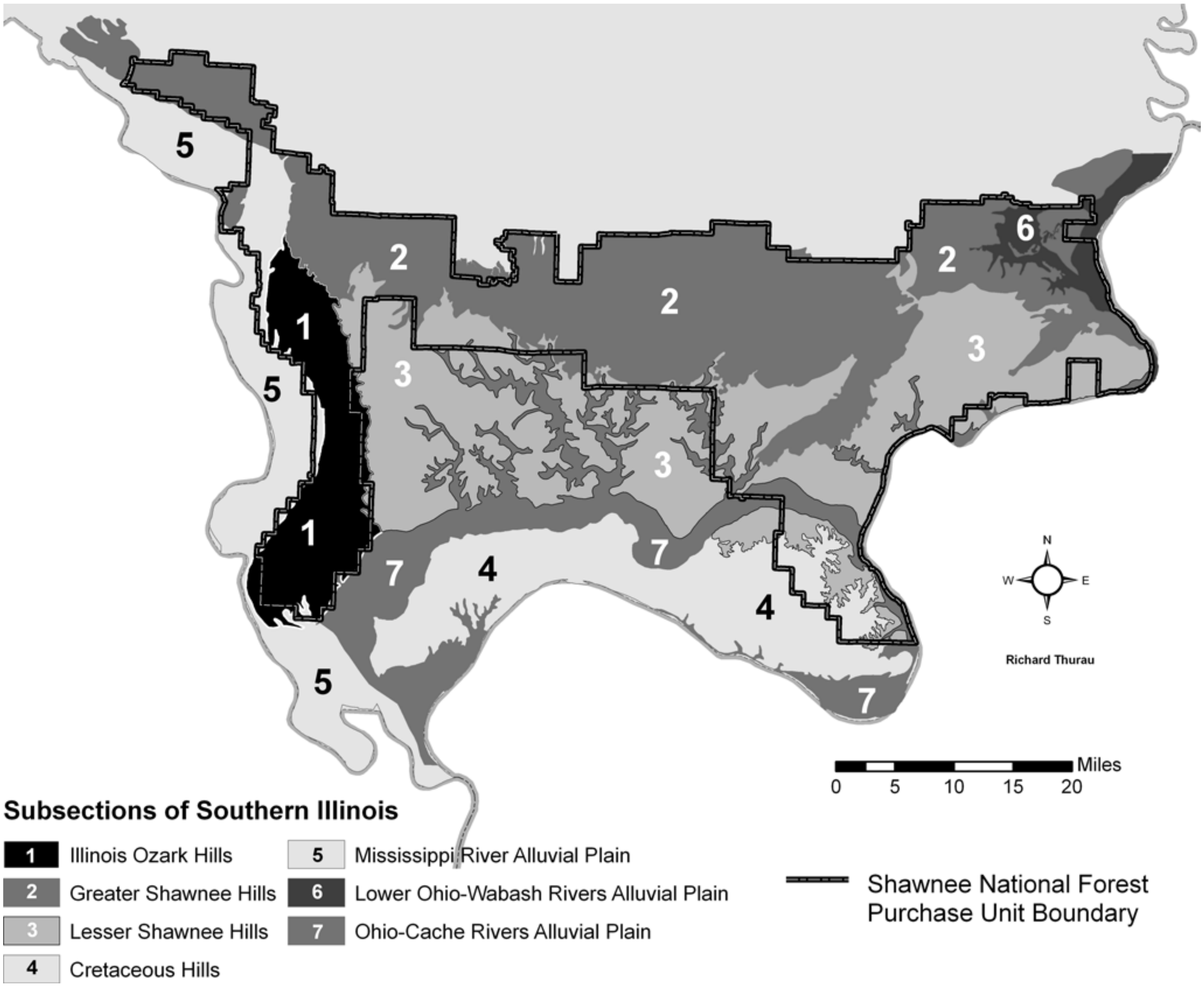


Figure 2.—The seven subsections of the Shawnee National Forest. This report focuses on the Illinois Ozark Hills subsection (1).

Previous work completed by Fralish and others (2002) provided a base for mapping the spatial distribution of forest types in the Shawnee. Although the previous characterization lacked the use of soil types and was based on coarse-resolution geographic data, ELT classes roughly estimated the parameters that have proven essential in the present study.

For this analysis, ELT delineation was based on physical land form and soil properties. Topographic features including hill slope percent, aspect, and curvature were derived and analyzed to define several ELT classifications. Additionally, soil series from alluvial parent material and alluvial soils classified as poorly and very poorly drained were identified as having spatial characteristics that effectively defined ecological site conditions.

Mapping ELTs with GIS

ELTs were delineated in a GIS with an automated model constructed and processed using ArcGIS 9.2 Modelbuilder (Environmental Systems Research Institute, Redlands, CA, 2006). All model parameter decisions are set before beginning any model process. Automation of the model was essential. First, automation allowed for changes to the model without requiring a reprocess of every model step. Second, an automated model will serve as a product for USFS personnel or other researchers who may recalculate ELTs as updated data become available.

Two data inputs were used to calculate ELTs for the entire Shawnee National Forest. Each of the 90 processes within the ELT model can be broadly categorized into one of three classes of tools: (1) Filtering tools used to reduce data artifacts, enhance the visual quality of output, and eliminate mapping units that were smaller than the spatial data precision; (2) Calculating tools used to combine and reclassify raster datasets and calculate topographic and geometric statistics of raster zones and vector polygons; and (3) Conversion tools utilized to aggregate zones of desired values into contiguous units.

Spatial Data Analysis and Preparation

Topographic and geometric landform characteristics were calculated from the National Elevation Dataset (NED) (USGS 1999) at approximately 10-m raster resolution for the study area. The NED represents the best available elevation datasets derived from a variety of sources and processes. Vertical accuracy of the 10 m NED datasets is considered to be +/- 7 to 15 m (USGS 1999).

Alluvial and poorly drained alluvial soils were identified from the Soil Series Geographic Database (SSURGO) made available by the U.S. Department of Agriculture, Natural Resource Conservation Service (NRCS 2005). SSURGO datasets are precisely digitized versions of paper soil series maps derived in the 1960s by the USDA. The NRCS states that SSURGO accuracy is as good as the paper series maps. SSURGO datasets for Randolph, Jackson, Williamson, Saline, Gallatin, Union, Johnson, Pope, Hardin, Alexander, Pulaski, and Massac Counties in Illinois were utilized in this analysis. Bryan Fitch, Soil Scientist at the Carbondale Major Land Resource Areas office, provided lists of soil series classified as alluvial and poorly drained alluvial soils. (Bryan Fitch, Personal communication, 2005-2007, Bryan.fitch@il.usda.gov)

ELT Classification

Six ELTs were derived in a GIS within the Ozark Hills subsection. General methodology for delineating ELTs by geomorphic characteristics is illustrated in a flow chart (Fig. 3). As part of data preparation SSURGO datasets were reduced to alluvial and poorly drained alluvial soils and classified as Alluvial Soils (ELT 5) and Poorly Drained Alluvial Soils (ELT 6).

Several derivatives of elevation datasets were utilized to delineate ELTs 1 through 4. Percent slope, hill slope aspect, and hill slope curvature were calculated and incorporated into ELT delineation. Slopes with a steepness of 14 percent or greater were classified as "slopes". "Slopes" were then further refined as either north- or south-facing and classified as North Slopes (ELT 3) or South Slopes (ELT 4) (see Fig. 3 for detailed classification criteria). Of the remaining areas, land units that have a gentle steepness gradient and are adjacent to alluvial soils (ELT 5 or ELT 6) or are mostly flat to concave are classified as Mesic Slopes (ELT 2). Remaining upland, convex areas are classified as Ridges (ELT 1).

Topographic and Geometric Characterization of ELTs

Zonal tools were used to calculate the topographic and geometric characteristics of each ELT. A zone in a raster dataset can be defined as an area, contiguous or disaggregated, that has the same value. Therefore, while ELTs are widely dispersed throughout the Ozark Hills subsection, each ELT represents a zone (i.e., there are six zones in the Ozark Hills, one for each ELT). Topographic and geometric statistics were calculated for each zone to characterize each ELT within the subsection.

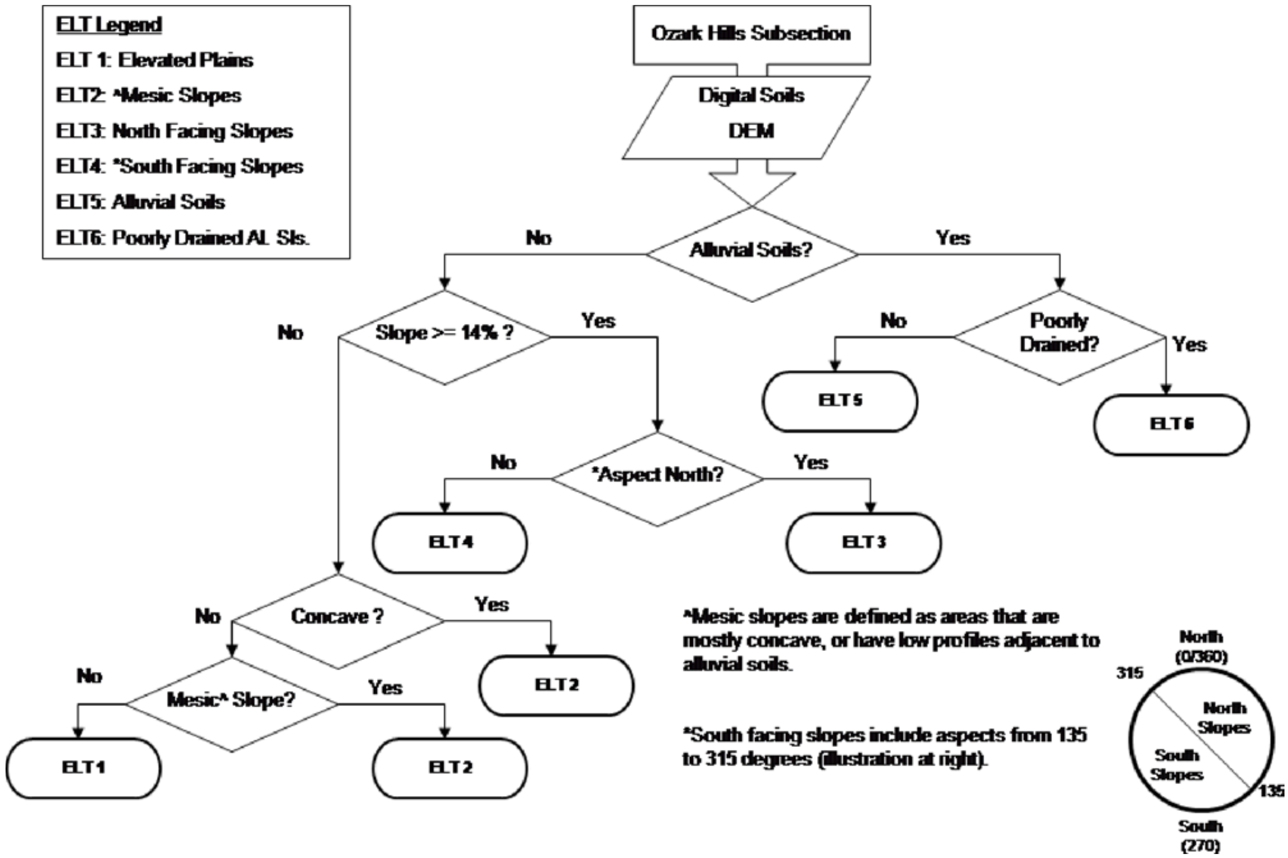


Figure 3.—Flow chart for ELT spatial unit delineation.

The products of this research are twofold: First, descriptive statistics are provided to geographically and geometrically characterize each ELT. These results are presented in Tables 1 and 2. Secondly, a GIS is utilized to combine ELT mapping results with datasets familiar to land managers to provide usable maps of ELT locations. Examples are provided in Figure 4.

Results recorded in Tables 1 and 2 identify the geometric and geographic characteristics of each ELT. Table 1 reports the spatial descriptive statistics averaged for all contiguous ELT units (polygons). Total area describes the aggregated coverage of all units for each ELT within the Illinois Ozark Hills subsection. Unit count, mean area, and standard deviation were summarized for all contiguous units in each ELT.

Table 2 reports descriptive spatial statistics based on geographic characteristics calculated for each raster pixel classified in each respective ELT and averaged over the entire study area. Minimum, maximum, range, and mean values are reported for elevation, landform curvature, and hill slope to geographically characterize each ELT. Elevation values are presented as elevation in meters above the geoid. Landform curvature ranges from negative (concave) to zero (flat) to positive (convex), and is used here to characterize the tendency of the geographic area represented by each pixel to shed or hold surface moisture. Hill slope is reported in percent and characterizes a site's soil moisture availability through water retention (low slope percent) or repulsion (high slope percent), as well as soil temperature in relation to solar radiation reflectance.

Table 1.—Geometric descriptive statistics as they characterize each of six ELTs in the Ozark Hills subsection

Spatial Characteristics:		Total Area		Unit Count	Mean Area per Unit	Stan. Dev. of Unit Area
ELT[1]		(Thousand sq. km)	(percent)	(number of polygons)	(sq. meters)	(sq. meters)
4	South Slopes	1.57	34%	3,010	52,195	161,566
3	North Slopes	1.38	30%	3,735	37,053	109,337
5	Alluvial Soils	0.78	17%	816	95,901	829,194
1	Ridges	0.44	10%	2,858	15,521	94,787
2	Mesic Slopes	0.35	8%	3,759	9,413	30,878
6	Poorly Drained A.S.	0.05	1%	105	49,210	157,862
	Total	4.59	100%	14,283	259,294	-

[1]ELTs ranked by total area.

Table 2.—Elevation, curvature, and percent slope as they vary by ELT in the Ozark Hills subsection

Elevation (meters)

ELT		Min	Max	Range	Mean
1	Ridges	99	314	215	168
3	North Slopes	91	311	220	165
4	South Slopes	90	310	220	165
2	Mesic Slopes	90	261	171	143
5	Alluvial Soils	91	237	146	131
6	Poorly Drained A.S.	95	172	77	109

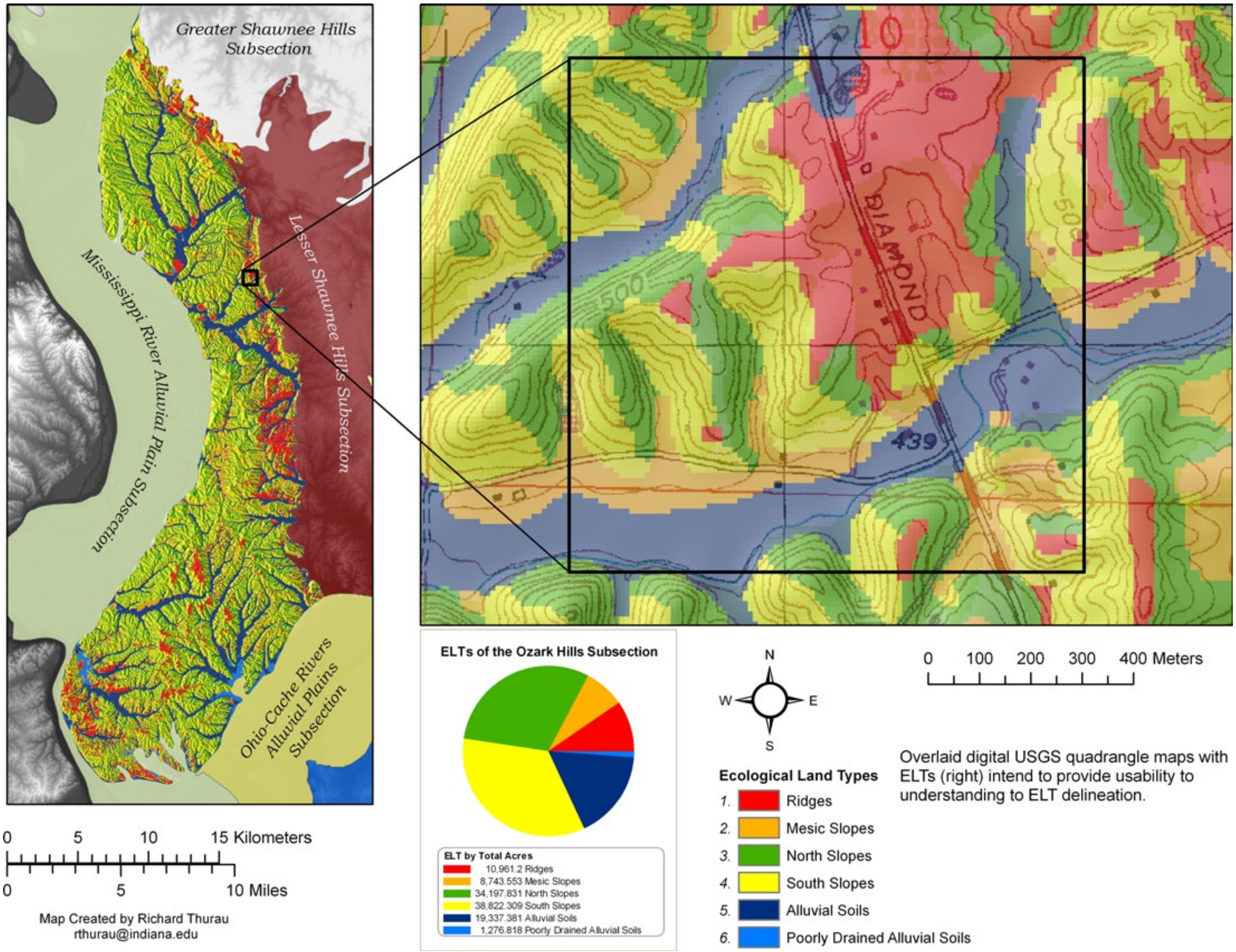
Landform Curvature (curve units)[1]

ELT		Min	Max	Range	Mean
1	Ridges	-8	7	15	0.25
3	North Slopes	-40	40	80	0.10
4	South Slopes	-28	26	54	0.02
6	Poorly Drained A.S.	-17	26	43	-0.10
5	Alluvial Soils	-11	10	21	-0.23
2	Mesic Slopes	-8	8	16	-0.25

Hill Slope (percent)

ELT		MIN	Max	Range	Mean
3	North Slopes	0	188	188	28
4	South Slopes	0	184	184	26
2	Mesic Slopes	0	48	48	10
1	Ridges	0	41	41	10
5	Alluvial Soils	0	72	72	7
6	Poorly Drained A.S.	0	169	169	4

[1]Curvature ranges from concave (negative) to flat (zero) to convex (positive).



a

b

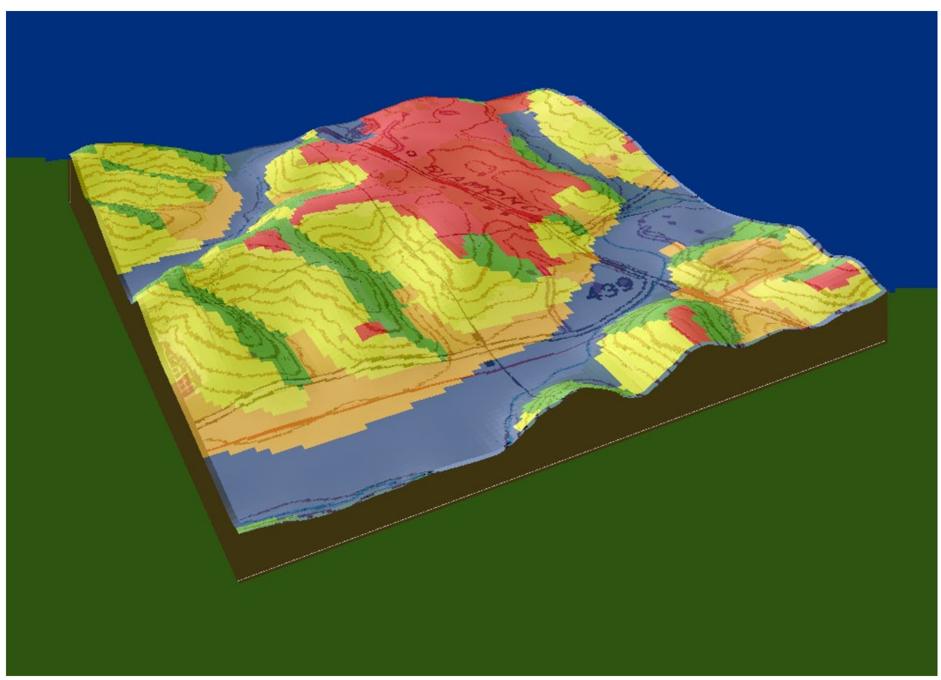


Figure 4.—ELTs in the Ozark Hills subsection. A zoomed-in subset (a) allows the viewer to discern features found on a typical USGS quadrangle map for relating on-the-ground observations with mapping units, while (b) three-dimensional rendering eases usability.

RESULTS

General results from Table 1 illustrate that the Illinois Ozark Hills subsection landscape is dominated by steep slopes (ELTs 3 and 4), but all ELTs vary greatly in total area, number of contiguous units, and average size per unit. Table 2 indicates that elevation may not be a good indicator of ELT except for ELT 6. Landform curvature is a subtle measurement, but may be a good indicator to differentiate between mesic and non-mesic site conditions, as the three mesic ELTs (2, 5, and 6) have an average concave value and non-mesic ELTs (1, 3, and 4) have an average convex value. Slope separation between ELTs is inherent in the model (as reported in the Methods), but Table 2 confirms the intuitive assumption that alluvial soils (ELTs 5 and 6) are substantially flatter than either ridges or mesic slopes (ELTs 1, 2, 5, and 6 are modeled under the same slope category).

Results from Table 1 illustrate that ridges (ELT 1) cover a relatively small portion (10 percent) of the Illinois Ozark Hills subsection, and are composed of nearly 3000 individual units, which have a relatively small average size. Standard deviation of polygon size is very large for all ELTs, indicating a wide variation in ELT size across the subsection.

Mesic slopes (ELT 2) also cover a small geographic portion of the study area, and are composed of the greatest number of polygons. Mesic slopes also are characterized as having the smallest average size per contiguous unit and the lowest standard deviation between unit areas.

North- and south-facing slopes (ELTS 3 and 4) cover the greatest proportion of the land area (64 percent combined) in the Illinois Ozark Hills subsection and sum to nearly half the total number of contiguous units. South facing slopes are, on average, larger than north facing slopes, and have a higher standard deviation between unit areas.

Alluvial soils (ELT 5) rank third in total area but are composed of substantially fewer polygons. That translates to a very large average unit size (nearly twice as big as the next largest), and a large standard deviation.

Poorly drained alluvial soils (ELT 6) are characterized to capture the most mesic areas on the landscape. Poorly drained alluvial soils represent a very small portion of the total study area (about 1 percent) and contain the fewest number of contiguous units, but unit size and standard deviation are about average among all ELTs.

CONCLUSIONS

USFS personnel have been directly involved with this project from its beginnings to ensure the maintenance of usability and applicability during the ELT development process. Non-spatial ELT characteristics (Tables 1 and 2) are likely too broad to be useful in the field but may provide important information for assessing potential management structure and for comparing ecological conditions among all seven subsections in the Shawnee.

Ultimately, it is the production of interpretable maps of ELTs with precise geographic boundaries that will be most useful to land managers. Mapping and GIS have the inherent ability to spatially relate relatively abstract concepts, such as ELTs, to something material and recognizable (i.e., the ability to drive to the field, point to a hillside, orient the map, and say "That is a South slope ELT"). Three-dimensional rendering of small geographic areas can relate important qualitative information quickly (Fig. 4b).

Designing an automated model (i.e., all model parameter decisions are set prior to beginning any model process) for ELT delineation was important for several reasons. The most important reason, and greatest constraint, was time. While this analysis examined results for the Illinois Ozark Hills subsection, ultimately our objective is to understand ELTs across every area within the entire 850,000-acre purchase-unit boundary. Secondly, this model will ultimately be delivered to USFS personnel as an operational tool. Therefore, ELTs can be delineated using the model at any time in the future, with the best available data. As stated by Regional Forester, Randy More, "The ecological, social and economic conditions on the Forest change over time. The public's opinions of what constitutes the best use of public lands also shifts over time. For these reasons, the management direction…is dynamic and will be re-evaluated periodically as new information becomes available" (Shawnee ROD 2006).

The diversity of criteria implemented in the development of ecological classification systems across the world varies greatly. While soils and landform characteristics determined delineation in this system, additional variables such as land use, property ownership, proximity to access or population centers, and more can be utilized or added to enhance our ideas of what ecological conditions will exist on specific parcels of land at any period in time.

Relationships between forest species and abiotic ecological conditions in the Shawnee are well understood. However, relating those ecological conditions to function within a GIS can present great challenges. As part of the development process, defined ELTs were mapped and visited at several locations. Qualitative observations and feedback were important in deciding how ELTs would be delineated.

Model validation with direct field sampling is yet to be conducted. Several datasets with spatial ecological information already exist within the study area. Historical witness tree data recorded in the early 19th century by the General Land Office Survey have been digitized for the entire Shawnee National Forest, and will provide the greatest geographic coverage for future model validation.

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STAND LEVEL HEIGHT-DIAMETER MIXED EFFECTS MODELS: PARAMETERS FITTED USING LOBLOLLY PINE BUT CALIBRATED FOR SWEETGUM

Curtis L. VanderSchaaf[1]

Abstract.—Mixed effects models can be used to obtain site-specific parameters through the use of model calibration that often produces better predictions of independent data. This study examined whether parameters of a mixed effect height-diameter model estimated using loblolly pine plantation data but calibrated using sweetgum plantation data would produce reasonable predictions of sweetgum. Results showed model calibration resulted in sound predictions of arithmetic mean height for the sweetgum data used in model calibration. However, data at older ages did not occur along the same general linear trend as the younger data used in calibration resulting in poor predictions. It should not be concluded that a mixed models framework using different species in model fitting and calibration will produce poor results. Poor predictions probably were obtained at older ages because the data used in calibration were too young and not because the parameter estimates using loblolly pine could not be calibrated for sweetgum.

INTRODUCTION

Growth and yield models are an integral component of forest management. Models help managers identify the productive capability of a particular species and how different cultural treatments will likely affect economic returns. Mixed models are becoming a popular modeling tool to provide more site-specific predictions of stand development. Both linear and nonlinear mixed models have been used in the development of natural resource models (e.g., Lynch and others 2005, Trincado and Burkhart 2006, Trincado and others 2007, VanderSchaaf and Burkhart 2007). Mixed effects models provide an efficient means to obtain cluster-specific, or for this particular example, stand-specific, parameters through the prediction of cluster-specific random effects. For example, arithmetic mean height (H) can be predicted as a function of quadratic mean diameter (D_q):

$$\ln H = \beta_0 + \beta_1 \ln D_q + \varepsilon \qquad [1]$$

where ln - natural logarithm, H - arithmetic mean height (ft), D_q - quadratic mean diameter (in.), β_0,β_1 - parameters to be estimated, ε - random error, where it is assumed $\varepsilon \sim N(0, \sigma^2 I)$.

Equation [1] provides what is often termed a population average estimate of H for a given D_q. We assume that the parameters β_0 and β_1 are fixed, or that the parameter estimates apply to every experimental unit (e.g., stand) in a population. Whether a stand is located in Florida or Arkansas, the parameter estimates are assumed to be correct. However, stand-specific characteristics such as soil type, nutrient status, competition from herbaceous vegetation, elevation, aspect, and genetic stock may cause parameters to differ across stands. Thus, specific stands may have what are generally termed “random parameters” in mixed effects

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model terminology. Equation [1] can be altered by adding stand-specific random effects to the population average parameters to produce stand-specific parameters:

$$\ln H = (\beta_0+u_{0i})+(\beta_1+u_{1i})\ln D_q + \varepsilon \qquad [2]$$

where u_{0i},u_{1i}- stand-specific random effects, assumed to be $N(0,\sigma_0^2)$ and $N(0, \sigma_1^2)$, respectively;, (β_0+u_{0i}) - stand-specific intercept; (β_1+u_{1i}) - stand-specific slope; i - index for a specific stand; and all other variables as previously defined.

Additionally, a covariance, σ_{01}, can be assumed to exist between u_{0i} and u_{1i}, where the parameter is assumed to be N(0). In this particular case, linear mixed effects models produce an efficient estimate of stand-specific parameters because only five parameters are estimated using the model-fitting algorithm (β_0, β_1 σ_1^2, σ_1^2, σ_{01}). Based on the variance and covariance estimates, and Bayesian methodology, we can predict stand-specific random effects (u_{0i},u_{1i}) and then add them to the population average intercept and slope (β_0,β_1) estimates to obtain stand-specific parameters. The prediction of stand-specific random effects is conducted outside the model-fitting algorithm and thus degrees of freedom are not lost. A much less efficient means of obtaining stand-specific parameters would be to estimate parameters separately for each stand. Although the parameter estimation efficiency of mixed models is an advantage, often the greatest advantage is the ability to calibrate the model using data independent of those used in model fitting.

Although several mixed effects models have been developed, no study has examined whether parameters fit using data from one species can be used to obtain cluster-specific random effects of another species. The advantage of using parameters from a species where more complete data in terms of stand ages, planting densities, site qualities, stand development, etc. exist is that more reasonable extrapolations of stand development for another species may be obtained. Cluster-specific random parameters depend on the amount of estimated variability in the random effects and the population average parameter estimates. Thus, differences in site requirements, structural constraints, growth habits, etc. among species may not allow for mixed effects models fit using one species to produce reasonable predictions of stand development for another species. This situation may occur when the population average parameter estimates of the model fitting species are not correct for the model calibration species, and/or the variability in the cluster-specific random effects of the model fitting species is not representative of the variability in the model calibration species.

Loblolly pine (*Pinus taeda* L.) is one of the most commercially important species in the Southeastern United States. Several long-term studies have been initiated and many growth and yield models have been developed for this species. Sweetgum (*Liquidambar styraciflua* L.) can generate revenue for a landowner but to a much smaller extent than loblolly pine. Hence, very few growth and yield models have been developed to predict stand development of plantations for sweetgum. Unlike many other hardwood species, sweetgum has a growth habit similar to loblolly pine. Sweetgum trees when young have a strong excurrent growth habit. They have conically shaped crowns and self-prune well (Kormanik 1990). Additionally, sweetgum is intolerant of shade and is therefore a relatively fast-growing species similar to loblolly pine. Thus, it may be possible to fit a mixed effects model using loblolly pine data and then to calibrate the model using sweetgum data to obtain reasonable predictions of future sweetgum stand development. It is the objective of this paper to determine the feasibility of using this approach to predict the height-diameter relationship of sweetgum plantations.

METHODS

Data Used in Model Fitting

Tree and plot measurements were obtained from long-term studies of planted loblolly pine and sweetgum in southeastern Arkansas. Observations of H and D_q were obtained from permanent research plots located in a loblolly pine plantation near Monticello, AR (http://www.afrc.uamont.edu/growthyield/montthinprun/index.html). The stand was planted in 1958 at a spacing of 8 ft square using 1-0 seedlings obtained from a state nursery located in Arkansas. Genetic stock was of a local seed source. Plots were originally established in 1970 and were measured at age 12 prior to conducting various thinning and pruning treatments. Thinning treatments from below at age 12 removed trees until residual basal areas per acre of 40, 60, 80, and 100 sq ft were obtained. At ages of 15, 24, 27, 30, 35, and 40, thinning treatments reduced basal areas to 30, 50, 70, and 90 sq ft per acre. Pruning treatments consisted of branch removal up to heights of 25, 40, and 50 percent of total tree height at ages 12 and 15. These thinned and pruned plots were also measured at ages 16, 19, 37, 43, 45, and 48. All observations used in model fitting were plot-level values obtained just prior to thinning treatments. Unthinned control plots were established in 1984, measured at age 27, and then remeasured at ages of 30, 35, 37, 40, 43, 45, and 48. Table 1 provides a summary of plot-level characteristics across all inventory ages and treatments. Site index was determined to be near 62 ft (base age 25).

Table 1.—Plot-level characteristics of the loblolly pine model fitting dataset (n = 559), and the sweetgum model calibration and fitting (equations 1 and 3) dataset (ages 5, 6, 7, and 8) and the sweetgum model validation dataset (ages 14 and 15). Where: Min—minimum, Max—maximum, Age—from seed, TPA—trees per acre, QMD—quadratic mean diameter, BAA—basal area per acre, H—arithmetic mean height.

Age		TPA	QMD (in.)	BAA (sq ft)	H (ft)
		Loblolly pine			
	Min	10	5.5	22	34
	Mean	127	14.8	80	69
All ages	Max	728	27.7	188	99
		Sweetgum			
	Min	312	1.7	7	10
	Mean	427	2.0	10	11
5	Max	513	2.3	14	13
	Min	312	1.9	8	13
	Mean	409	2.3	12	14
6	Max	491	2.6	17	17
	Min	290	2.5	11	15
	Mean	391	2.7	16	17
7	Max	491	3.2	26	21
	Min	268	3.1	17	19
	Mean	382	3.5	25	21
8	Max	468	3.9	37	25
	Min	245	4.6	34	31
	Mean	363	5.0	49	38
14	Max	446	5.5	69	44
	Min	245	5.0	39	37
	Mean	366	5.4	57	41
15	Max	446	6.1	76	48

For sweetgum, observations of H and D_q were obtained from permanent research plots established in 1979 in an unthinned plantation located near Monticello, AR, using 1-0 seedlings of local seed source planted at a 9 ft square spacing (Ku and others 1981, Guo and others 1998). Fertilizer treatments (N only [205 lb N/ac], P only [123 lb P/ac], and the combination of the two nutrients) and controls were established when the plantation was 4 yrs old. Trees were measured beginning at age 5 and remeasured at ages of 6, 7, 8, 14, and 15. After fertilization at age 4 no additional treatments were applied. Table 1 provides a summary of plot-level characteristics by plantation age. The natural fertility is moderate and the site index was determined to be 80 ft at base age 50 (Guo and others 1998).

Table 2.—Population average (β_0 and β_1) parameter estimates and associated standard errors and random effects variance (σ^2_0, σ^2_1) and covariance (σ_{01}) parameter estimates for the final mixed-effects model. There were a total of 559 observations used in model fitting and the total number of clusters was 45. Parameter estimates for equations [1] and [3] using the sweetgum model fitting dataset (ages 5, 6, 7, and 8, n = 96) are also given along with their associated standard errors. Where: -2LL—twice the negative log-likelihood, AIC—Akaike's Information Criterion, MSE—mean square error, and Adj. R^2 is the adjusted R^2.

Validation results when predicting arithmetic mean height as a function of quadratic mean diameter for the sweetgum ages of 14 and 15 are also provided (n = 48). Eqn. [1]—sweetgum refers to using OLS to estimate parameters when pooling data from all plots using ages 5, 6, 7, and 8, while Eqn. [1]—individual sweetgum plots refers to using OLS to estimate parameters separately for each individual plot using ages 5, 6, 7, and 8.

	Model fitting results							
	Mixed—loblolly pine		Eqn. [1]—sweetgum		Eqn. [3]—sweetgum		Eqn. [1]—individual sweetgum plots	
Parameter	Estimate	SE	Estimate	SE	Estimate	SE		
β0	2.2336	0.0293	1.6877	0.0392	0.8215	0.1144	-	-
β1	0.7563	0.0147	1.1080	0.0405	0.5350	0.0795	-	-
β2	-	-	-	-	0.7586	0.0966	-	-
σ^2_0								
σ^2_1	0.0297	-	-	-	-	-	-	-
σ_{01}	0.0084	-	-	-	-	-	-	-
	-0.0149	-	-	-	-	-	-	-
-2LL	-1672.0000		-191.8000		-236.9000		-	
AIC	-1664.0000		-		-		-	
MSE	0.0019		0.0071		0.0043		-	
Adj. R^2	-		0.8886		0.9330		-	
							Model validation results	
Bias	8.8400		5.7700		-2.4500		4.8800	
Variance	4.4500		5.6100		5.1200		10.3900	
MSE	82.5200		38.8700		11.1400		34.2500	

Model Development and Parameter Estimation

Parameters of equation [2] were estimated for the loblolly pine plantation dataset using SAS Proc MIXED (Littell and others 1996), which assumes random errors are normally distributed and subsequently estimates parameters using maximum likelihood. Rather than simply assuming β_0 and β_1 were random across plots, likelihood ratio tests were conducted to determine if assuming β_0 was random, β_1 was random, and if assuming a covariance term existed between u_{0i} and u_{1i} (σ_{01}), produced better model fit statistics. For the sake of brevity, complete likelihood ratio test results are not presented. Based on likelihood ratio tests and Akaike's Information Criterion, a model where both β_0 and β_1 were considered to vary across plots and which includes a covariance term, σ_{01}, was found to be best (Table 2).

In many cases random effects account for nearly all autocorrelation among observations when using longitudinal datasets (Trincado and Burkhart 2006, VanderSchaaf and Burkhart 2007, Vonesh and Chinchilli 1997); however, a modeler can also directly model the random error structure. When parameters are estimated in a mixed-effects model framework using data from one species and calibrating for another, the measurement intervals may not be the same among the datasets. This difference can cause problems when trying to estimate covariances of the random errors because a covariance structure that is appropriate for the model fitting dataset may not be appropriate for the model calibration dataset. For this particular study, since measurement intervals differed among the datasets, the random error covariance-variance matrix was assumed to be $\sigma^2 I$.

To determine whether a mixed effects model fit using loblolly pine and calibrated using sweetgum would produce better predictions of H than a conventionally estimated height-diameter equation using sweetgum, parameters of equation [1] were estimated. The conventional approach is to use data of the species of interest, which in this case is sweetgum, and ordinary least squares. To account for the impacts of fertilization and stand density on the height-diameter relationship, a second conventional equation was developed that included age as an additional regressor:

$$\ln H = \beta_0 + \beta_1 \ln D_q + \beta_2 \ln Age + \varepsilon \quad [3]$$

where Age—years from seed (plantation age plus 1 year), and all other variables as previously defined.

Data used in estimating parameters of equations [1] and [3] were the same data used in calibrating equation [2], ages 5, 6, 7, and 8 from the sweetgum plantation. Proc Mixed of SAS (SAS Inc, Cary, NC) was used to estimate parameters. Initial attempts were made to include basal area per acre rather than age in equation [3], but the basal area parameter was highly non-significant (alpha level = 0.4674).

Prediction errors were compared between the three approaches using the sweetgum data at ages of 14 and 15 and the validation process proposed by Arabatzis and Burkhart (1992). The difference between the observed and predicted arithmetic mean height($e_{ij} = H_{ij} - \hat{H}_{ij}$)for each individual plot (i) and age (j) was calculated for all three parameter estimation approaches. The mean residual ($\bar{e}$) and the sample variance (v) of residuals were computed and considered to be estimates of bias and precision, respectively. An estimate of mean square error (MSE) was obtained combining the bias and precision measures using the following formula:

$$MSE = \bar{e}^2 + v$$

Values of MSE were compared between the three approaches (equation [1] fit using sweetgum data, equation [3] fit using sweetgum data, equation [2] fit using loblolly pine data but calibrated using sweetgum data) to determine which one was most appropriate for this particular sweetgum plantation dataset. To account for logarithmic transformation bias, the procedure recommended by Baskerville (1972) and also described by Trincado and others (2007) was used. All validation statistics presented in this paper are based on untransformed errors.

RESULTS AND DISCUSSION

All three modeling (equations [1]—[3]) approaches produced bias predictions of H when extrapolating beyond the range of data used in model calibration or fitting (Table 2). The sweetgum-calibrated mixed effects model produced the most bias, resulting in the greatest MSE. However, using a mixed effects model actually produced the lowest variance in predictions.

Figure 1 demonstrates that model calibration of equation [2] resulted in sound predictions of H for the sweetgum data used in model calibration. However, Hs at ages of 14 and 15 were not on the same linear

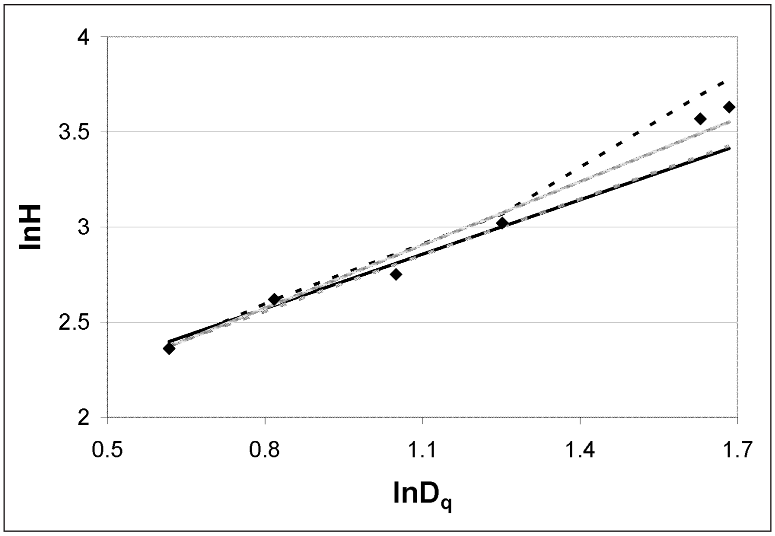

Figure 1.—Observed values of logarithmically transformed arithmetic mean height and quadratic mean diameter at ages 5, 6, 7, 8, 14, and 15 for the phosphorus-treated plot in block 1 (diamonds). The solid black line are predictions using a mixed effects calibrated model (equation 2), the dotted black line are predictions using equation [3], the solid gray line are predictions using equation [1] when pooling data from all plots, and the dotted gray line are predictions using equation [1] fit specifically to observations at ages 5, 6, 7, and 8 of this plot.

trend as Hs at ages of 5, 6, 7, and 8 and therefore predictions at ages of 14 and 15 were generally poor. Calibrated predictions were always less than the observed heights (Figs. 1 and 2). Equations [1] and [3] were most likely superior in predicting H at ages 14 and 15 because they ignored the trends of individual plots at ages of 5, 6, 7, and 8 and fit a model that better captured the general trend across all plots. If the Hs at ages 14 and 15 were on the same linear trend for individual plots as the Hs at ages 5, 6, 7, and 8, the mixed effects model would probably have been superior.

In an attempt to check the validity of the previous sentence, parameters using equation [1] were estimated for each individual sweetgum plot, and then validation statistics were conducted as described previously. Predictions using ordinary least squares (OLS) for each individual sweetgum plot produced less bias relative to the calibrated mixed effects model; however, the variance was much greater (Table 2). Overall, the MSE was less when estimating parameters using OLS for each individual plot compared to a mixed effects model framework. However, similar to the calibrated mixed effects model, the two conventional approaches often resulted in better predictions at ages 14 and 15 than OLS fits of each individual plot using younger data. Figure 1 shows that indeed parameter estimates using OLS based on data from this particular plot at ages 5, 6, 7, and 8 failed to capture the general trend at ages 14 and 15 (in fact the OLS and calibrated mixed effects model essentially follow the same trend). Thus, for this particular sweetgum dataset, the use of younger ages both to calibrate a mixed effects model and to estimate parameters by means of OLS produced poor predictions at older ages since all data were not on the same linear trend. Perhaps a non-linear model would have produced better results; however, the logarithmic transformation was used to help linearize the data. For either of the four approaches, prediction errors do not appear to be related to D_q (Fig. 2).

These results demonstrate that a mixed effects model calibrated for a species other than the one used in model fitting will produce very good predictions of the data used in model calibration. However, this study shows that when extrapolations beyond the range of data used in model calibration may yield very poor predictions. These results probably were observed not because loblolly pine was used in the mixed effects model fitting, but rather because the sweetgum data at older ages were not on the same linear trend as the younger sweetgum data used in model calibration (perhaps resulting from decreases in diameter increment at older ages due to excessive stand density). This observation is demonstrated by the poor MSE

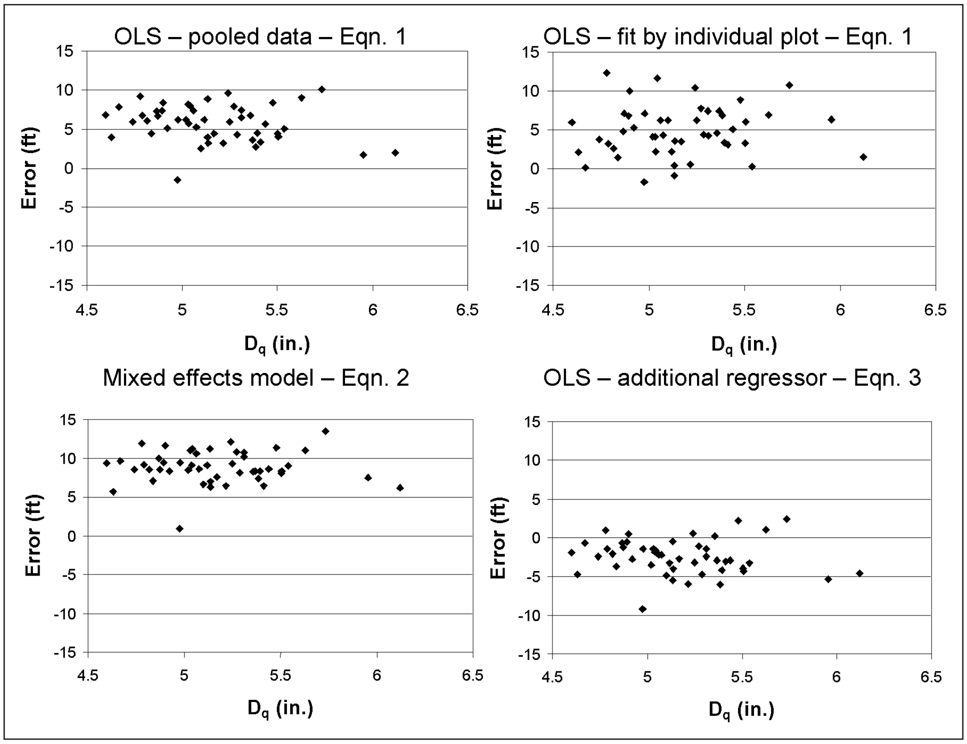

Figure 2.—Untransformed errors when predicting arithmetic mean height at ages of 14 and 15 for equation [1] when estimating parameters for each individual plot, equation [1] when pooling data from all individual plots, and for equations [2] and [3]. n = 48 for each predictive alternative.

results even when estimating parameters for each sweetgum plot using OLS (Table 2 and Fig. 1). Results from this study, as well as similar unpublished calibration studies conducted by the author, demonstrate that calibrating a mixed effects model using young data and extrapolating to older ages may produce poor results. Perhaps if the 14- and 15-year-old data were used in model calibration along with the ages of 5, 6, 7, and 8, predictions at ages of 20 and 25 would be better. Although height measurements were obtained at older ages for this sweetgum study, an ice storm reduced the tops of many trees at age 19. Thus, damage from the ice storm would be a confounding factor if data from these older ages were used.

It is not exactly clear why the data at ages of 14 and 15 were not on the same linear trend for individual plots. Perhaps a log transformation is not sufficient to produce linearity. The stands were fertilized a second time when they were 24 years old; thus fertilization was not a factor at ages 14 and 15.

In conclusion, results from this study demonstrate a mixed effects model fit using one species but calibrated for another did not produce adequate predictions when extrapolating beyond the range of data used in model calibration. This result was observed because data at ages 14 and 15 were not on the same general linear trend as the data used in model calibration, ages 5, 6, 7, and 8. It should not be concluded that mixed effect models do not produce adequate predictions and that a mixed effects model fit using one species cannot be calibrated for another species. Results from this study are additional evidence that users of models need to be careful when extrapolating beyond the range of data used in model fitting or model calibration. Further research needs to be conducted to determine if calibrating mixed effects models using data from young ages as well as during mid-rotation will produce adequate predictions for economic rotation ages.

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SILVICULTURE AND GENETICS

GRAPEVINE DYNAMICS AFTER MANUAL TENDING OF JUVENILE STANDS ON THE HOOSIER NATIONAL FOREST, INDIANA

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Abstract.—Large woody vines, most notably grapevines, are a source of great concern for forest and wildlife managers in many parts of the Central Hardwood Forest Region of the United States. We examined grapevine dynamics in stands aged 21 - 35 years. The plots, located in regenerated clearcuts in the Hoosier National Forest (HNF), were evaluated for vine control, site, and tree species colonization. Results showed that change in grapevine density from 1986 to 2004 was influenced by grapevine removal and aspect code. Grapevine density reduction was greater in plots from treated stands than in plots from untreated stands. In 2004, however, grapevine density was similar regardless of vine control. The observed reduction in grapevine density was higher in plots with a southwestern aspect. Grapevine association in 2004 was influenced by host species group and canopy class. Trees in the dominant canopy position had higher occurrence than those in the suppressed class. Nearly 30 percent of infested trees were black cherry, 13 percent were yellow-poplar, and 10 percent were oak. Black cherry also had the most vines, representing 19.8 percent of the total, followed by maple with 19.5 percent and yellow-poplar at 10.9 percent. Success of the vine control treatment applied on the HNF appears limited.

INTRODUCTION

Lianas, or large woody vines, most notably grapevines, are a source of great concern for forest and wildlife managers in many parts of the Central Hardwood Forest Region (CHFR). Vines grow under a wide variety of soil and site conditions throughout the region; they are particularly common on highly productive sites. Historically, most research concerning grapevines was centered on controlling grapevines in the cove hardwood type in the Appalachian region of the CHFR (Trimble and Tryon 1974, Trimble and Tryon 1979, Smith 1984), although more recently, research into the role of grapevines in even-aged management of oak-hickory type forests has also surfaced (Indiana Dept. of Nat. Resour. 1984, Fischer 1987).

Grapevines are an important habitat component in the region; they produce food and cover for many species of wildlife. It has been reported that black bear, raccoon, turkey, grouse, quail, and various songbirds feed on grape berries (Martin and others 1951). It is estimated that at least 80 species of birds eat grape berries, as does a host of other wildlife species (Shutts 1968). However, forest managers often view grapevines as a problem because of the threat they pose to growth and quality of developing timber, especially on high quality sites, where grapevines are often found (Trimble and Tryon 1979). Grapevines may damage trees by breaking limbs; twisting, bending, possibly even breaking tree boles; or uprooting trees. Grapevines also may pose a problem in wind storms or result in greater ice damage to tree tops and limbs (Smith 1984).

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Research on the structure and dynamics of natural liana communities in temperate forests is rather limited (Monsi and Ogawa 1977, Friedland and Smith 1982, Carter and Teramura 1988, Gartner 1991, Collins and Wein 1993, Putz 1995, Talley and others 1996, Allen and others 1997, 2005, Schnitzer and Bongers 2002, Pérez-Salicrup and others 2004, Londre and Schnitzer 2006), and it is especially limited in the CHFR (Trimble and Tryon 1979, Smith 1984, Beck and Hooper 1986) and Indiana (Standiford and Fischer 1980).

Even-aged management of forest stands and stand-replacing disturbances, as well as minor disturbances, often increase opportunities for the growth and proliferation of grapevines. The result of such disturbances provides grapevines with increased light, water and nutrient resources, trellises (downed woody debris and developing seedlings), and establishment opportunities. Grapevines are intolerant of shade and when exposed to sunlight, stems produce epicormic branches (Smith 1984). Vines root or layer easily when they come into contact with soil, and they sprout prolifically when cut or damaged (Smith 1984). Shutts (1968) reports that shoot growth is rapid; Trimble and Tryon (1979) observed that young grapevine stump sprouts grew 4.6 m in a single season. Grapevines are supported by tendrils that allow vines to attach and grow on vegetation, and Trimble and Tryon (1979) suggest that tendrils attach to tree crowns when trees are young, thus developing and proliferating in developing tree crowns.

OBJECTIVES

This is a continuation of a long-term study to evaluate regeneration of clearcut upland hardwood sites in southern Indiana. The study was established in 1986 by the U.S. Forest Service and led by Dr. B.C. Fischer on the Hoosier National Forest (HNC) in south-central Indiana. Forest stand composition and structure and grapevine occurrences were reported for clearcut stands aged 5 - 17 years by Fischer (1987). This study evaluates the dynamics of grapevines on a portion of the sites as they relate to site and species colonization in stands 21 to 35 years old. Grapevine species in the south-central Indiana region include summer grape (*Vitis aestivalis* Michx.), winter grape (*Vitis cinerea* (Engelm.) Engelm. ex Millard), fox grape (*Vitis labrusca* L.), riverbank grape (*Vitis riparia* Michx.), and frost grape (*Vitis vulpina* L.), though no distinction between species was made in recording grapevine occurrence.

STUDY AREA

This study was conducted within the HNF, an upland hardwood forest landscape in the unglaciated central portion of southern Indiana. The HNF is located within the Highland Rim and Shawnee Hills sections of the Interior Low Plateau (Homoya and others 1985). The 80,000 ha forest is divided between the Brownstown Ranger District, which is further subdivided between the Pleasant Run and Lost River management units, and the Tell City Ranger District, composed of the Patoka Lake and Tell City management units. For this study, we examined results only from the Shawnee Hills section of the HNF.

The Tell City and Patoka Lake management units fall within the Crawford Uplands subsection of the Shawnee Hills section, although Patoka Lake has area within the Escarpment subsection. The Crawford Uplands subsection is characterized by rugged hills of well drained, acid silt loams of the Wellston-Zanesville-Berks association formed from sandstone and loess, which are marked by sandstone outcrops and rock shelters. The Tell City management unit also includes areas of the Wellston-Zanesville-Tilsit association, which are only moderately well-drained and occur on less steep slopes. The soils are all considered moderately deep to deep (IDNR 1984). Oak-hickory (*Carya* spp. L.) is the dominant forest type on upland slopes. White oak (*Quercus alba* L.), black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Muenchh.), chestnut oak (*Q. montana* Willd.), and hickory species are typical of upland slopes, while more mesic species such as American beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), white ash (*Fraxinus americana* L.), yellow-poplar (*Liriodendron tulipifera* L.), and black walnut (*Juglans nigra* L.) are more common in coves and lower slopes.

The Escarpment subsection has sandstone outcrops and rock shelters that are not present as in the Crawford Uplands subsection, although much of the upland sections are otherwise similar in soils and topography. The Escarpment Subsection has limestone outcrops and lower areas may contain limestone-derived soils and karst topography. In the upland areas, post oak (*Q. stellata* Wangenh.) and black oak tends to replace chestnut oak on drier sites, while some of the cove species present on the Crawford Uplands subsection are absent in the Escarpment subsection.

METHODS

Sampling and Vine Control

In 1986, 74 stands were located and inventoried to evaluate regeneration of clearcut upland hardwood sites in southern Indiana (Fischer 1987). An abbreviated description of the 1986 methods is provided here, but a detailed description may be found in Fischer (1987). All sampled stands were selected based on the requirement that they were harvested between 1969 and 1982 and had complete management records, including age, acreage, and sawtimber volume by HNF species groups. Sampling was conducted between July 1986 and March 1987. Measurement plots were 0.004-ha circular plots with a resulting sample intensity of 1.0 percent. All trees and woody shrubs greater than 1.37 m were tallied by species, crown class, and origin (seedling, seedling sprout, stump sprout, or residual). All wild grapevines rooted within sample areas were tallied using the same procedure as Standiford and Fischer (1980); however, host tree species was not recorded.

In 2004, new plots were established because the 1986 plot centers could not be efficiently relocated. Plots were arranged at a density of 2.5 plots ha^{-1} for a sampling intensity of approximately 10 percent. Each plot consisted of a 0.04-ha plot where trees with a diameter at breast height (d.b.h.) of 2.54 cm and greater were measured. Species, d.b.h., and crown class (dominant, intermediate, suppressed) were recorded for each tree. The number of grapevines rooted in the plot and entangled in the canopy of a tree within the plot, and the tree in question, was also recorded. Aspect was recorded to the nearest 5° of azimuth. Aspect measurements were transformed using Beers and others (1966) transformation procedure; thus, four groups were derived, hereafter referred to as aspect code. Aspect codes 1 (185° to 265°) and 2 (135° to 185°, and 265° to 315°) range from southeast to northwest, and were typically more xeric sites, while aspect codes 3 (85° to 135°, and 315° to 5°) and 4 (5° to 85°), were more mesic sites, and denote aspects ranging from northwest to southeast. Slope percentage was recorded to the nearest 5 percent and later classified as slope code 1 (0 to 15 percent slope) and slope code 2 (16 to 30 percent slope). Slope position was recorded as upper, mid, and lower slopes. The change in grapevine density between 1986 and 2004 was calculated by subtracting grapevines ha^{-1} by plot in 2004 from the plot average (grapevines ha^{-1}) in 1986 for each treatment.

Manual tending of grapevines was conducted in 10 stands (233 plots) within the Shawnee Hills natural region, and these were compared to 40 stands (711 plots) that received no grapevine treatment. HNF contract regulations required that at least 90 percent of all grapevine stems be severed within 46 cm of the ground with no chemical application to severed stems. Stands were treated between 1986 and 1989, and they ranged in age from 11 to 18 years at the time of treatment, shortly after the beginning of the stem exclusion stage of stand development.

Table 1.—Mean change in grapevine density ha^{-1} from 1986 to 2004 as related to vine control, aspect, position code, and slope code for 50 stands of the Hoosier National Forest, IN

Factor	Category	No. plots	Mean ± SE	P-value	r^2
Vine Control				<.0001	0.311
	Untreated	711	628 ± 10		
	Treated	223	1139 ± 33		
Aspect Code				0.0355	0.009
	1	215	802 ± 24	0.0230	
	2	237	768 ± 27	0.4260	
	3	274	734 ± 25	0.4470	
	4	208	697 ± 25	0.0210	
Position Code				0.0805	0.005
	Lower	178	781 ± 28		
	Midslope	572	727 ± 15		
	Upper	184	791 ± 37		
Slope Code				0.4809	0.001
	1	836	753 ± 14		
	2	98	724 ± 39		

Statistical Methods

For changes in grapevine density over time, vine control, aspect code, position code, and slope code were analyzed separately with one-way analysis of variance using the GLM procedure of SAS (Version 9.1, SAS Institute Inc., Cary, NC). Contrasts were used to detect differences in levels of each factor. For grapevine occurrence and host species associations, all three factors (vine control, host species group, and canopy class) were tested in the same manner. Analysis of variance is fairly robust against departures from normality and unequal variance when sample size is large such as in this case; hence, data were not transformed after prior analysis.

RESULTS

Grapevine Density over Time

Change in grapevine density from 1986 to 2004 was influenced only by grapevine removal (P <0.0001, r^2 = 0.31) and aspect code (P = 0.035, r^2 = 0.09). The reduction in grapevine density was greater in plots from treated stands than in plots from untreated stands (Table 1). Grapevine density in plots from treated stands decreased from an average of 1404 ± 102 vines ha^{-1} to 265 ± 33 vines ha^{-1}, while grapevines in plots from untreated stands decreased from an average of 872 ± 32 vines ha^{-1} to 244 ± 10 vines ha^{-1} (Table 2, Fig. 1). Treated and control plots had similar density in 2004 (Table 2). Grapevine density reduction in aspect code 1 (xeric) was significantly greater than in all others, from an average of 999 ± 67 vines ha^{-1} to 199 ± 17 vines ha^{-1} (P = 0.023). Aspect code 4 (mesic) had the lowest reduction, from an average of 1027 ± 69 vines ha^{-1} to 278 ± 22 vines ha^{-1} (P = 0.021).

Grapevine Occurrence and Host Species Group

Grapevine occurrence in 2004 was influenced by grapevine removal (P < 0.0001, r2 = 0.001), host species group (P < 0.0001, r^2 = 0.026), and canopy class (P < 0.0001, r^2 = 0.030). Mean occurrence was 0.168 ± 0.005 vines $tree^{-1}$ in plots from treated stands versus 0.124 ± 0.002 vines $tree^{-1}$ in plots from untreated stands (Table 3). Contrasts showed all species group were significantly different from each other. Black cherry had

Table 2.—Mean grapevine density (vines ha^{-1}) in 1986 and 2004 as related to vine control, aspect, position code, and slope code for 50 stands of the Hoosier National Forest, IN

		1986		2004	
Factor	Category	No. plots	(Mean ± SE)	No. plots	(Mean ± SE)
Vine control	Untreated	904	872 ± 32	711	244 ± 10
	Treated	319	1404 ±102	223	265 ± 33
Aspect	1	266	999 ± 67	215	199 ± 17
	2	305	972 ± 62	237	253 ± 22
	3	342	1040 ± 85	274	264 ± 22
	4	310	1027 ± 69	208	278 ± 22
Position code	Lower	178	1271 ± 106	178	249 ± 23
	Midslope	906	983 ± 42	572	254 ± 12
	Upper	139	860 ± 82	184	248 ± 32
Slope code	1	1048	1039 ± 40	836	244 ± 11
	2	145	763 ± 72	98	295 ± 32

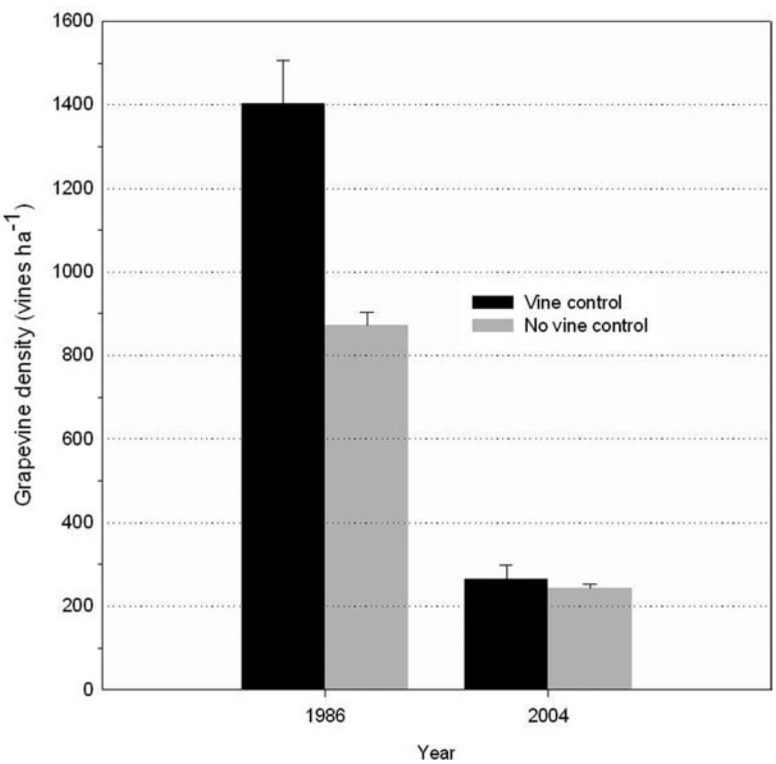

Figure 1.—Change in grapevine density from 1986 to 2004 in the Hoosier National Forest, IN, as influenced by manual tending of grapevines in 10 of the 50 stands.

by far the highest occurrence with 0.428 ± 0.012 vines tree^{-1} while other groups ranged from 0.08 to 0.18 vines tree^{-1} (Table 3). Canopy classes were also all significantly different from each other at the $P < 0.0001$ level, with highest occurrence in the dominant class and lowest in the suppressed class (Table 3).

Descriptive statistics showed that nearly 10 percent of all trees were infested with grapevines (Table 4); 30 percent of those infested were black cherry, 13 percent were yellow-poplar, and 10 percent were oak. While only 8.6 percent of trees in the other species group were infested, they comprised 41.4 percent of all vines tallied. A breakdown of the other species group showed that elm comprised 24.5 percent of that category (10.1 percent of total), followed by white ash with 15.6 percent and sassafras at 14.5 percent. Hence, black

Table 3.—Mean grapevine occurrence (vine $tree^{-1}$) in 2004 as related to vine control, species group, and canopy class for 50 stands of the Hoosier National Forest, IN

Factor	Category	No. trees	Mean ± SE
Vine control	Untreated	56,825	0.124 ± 0.002
	Treated	14,164	0.168 ± 0.005
Species group	Black cherry	4,351	0.428 ± 0.012
	Maple	21,504	0.085 ± 0.003
	Oak	6,435	0.124 ± 0.005
	Other species	33,050	0.118 ± 0.003
	Yellow-poplar	5,649	0.181 ± 0.007
Canopy class	Dominant	20,995	0.257 ± 0.004
	Intermediate	25,648	0.110 ± 0.003
	Suppressed	24,346	0.049 ± 0.002

cherry was the species with the most vines, representing 19.8 percent of the total, followed by maple with 19.5 percent and yellow-poplar at 10.9 percent.

DISCUSSION AND CONCLUSIONS

Throughout the Central Hardwood Region, wild grapevines are often considered an obstacle to quality timber production (Trimble and Tryon 1974, 1979, Smith 1984, Golden 2002). Trimble and Tryon (1974) identified four major concerns associated with grapevine invasion: 1) breakage of tops and limbs; 2) twisting and bending of stems; 3) smothering of trees and interference with photosynthesis thus decreasing growth; and 4) increasing damage by ice, snow, and wind. The high densities observed in the 1986 measurements confirm these concerns about the rapid growth of grapevines and their domination of patches within young stands of hardwoods. Both Smith (1984) and Golden (2002) identified thick patches of grapevine as the major deterrent to obtaining adequate regeneration in young hardwood stands following group selection, especially on better quality sites. Beck and Hooper (1986) also observed heavy grapevine densities following clearcutting, with more than 50 percent of their study plots heavily influenced by grapevines.

The strong association of grapevine presence and canopy class is not surprising considering its species' relative shade intolerance. Grapevines may exist in shaded conditions for a period of 2 to 5 years, but prolonged periods of shade reduce their growth and will eventually kill the vine (Smith 1984). Although grapevine density reduction was greatest on xeric aspects, the combination of high water-transport demands as indicated by the morphology of grapevines and a series of drought events between 1986 and 2004 (Morrissey 2006) may have influenced this finding.

A number of treatments, both preharvest and postharvest, are recommended for controlling grapevine densities (Smith 1984). In this study, the HNF used the 1986 results to identify stands with high grapevine densities and these stands were then treated. While density decline between 1986 and 2004 was significantly greater in treated stands (Table 1), densities in 2004 were similar in all stands (Table 2). Vine density declined in almost all stands in this study (treated or nontreated). Assuming control measures reduced grapevine density to the contract standards (minimum 90 percent reduction), an average of 140 grapevines ha^{-1} were present in the treated plots after 1986. We observed that grapevine density in these same treated plots was about 265 grapevines ha^{-1} in 2004, a density similar to that observed in

Table 4.—Descriptive summary of grapevine occurrence in 2004 as related to vine control, species group, and canopy class for 50 stands of the Hoosier National Forest, IN

Treatment	Canopy class	Species	No. trees	No. infested trees	Percent trees infested	No. vines	Percent total vines
None	Dominant	Black cherry	2498	930	37.2	1308	13.9
		Maple	2417	384	15.9	485	5.2
		Oak	3140	444	14.1	539	5.7
		Other species	5232	947	18.1	1256	13.3
		Yellow-poplar	3264	492	15.1	663	7.0
	Intermediate	Black cherry	936	193	20.6	247	2.6
		Maple	6556	452	6.9	542	5.8
		Oak	1691	111	6.6	131	1.4
		Other species	11095	855	7.7	1097	11.7
		Yellow-poplar	874	74	8.5	93	1.0
	Suppressed	Black cherry	102	5	4.9	8	0.1
		Maple	7617	152	2.0	212	2.3
		Oak	715	13	1.8	17	0.2
		Other species	10369	269	2.6	413	4.4
		Yellow-poplar	319	11	3.4	18	0.2
Vine control	Dominant	Black cherry	722	142	19.7	251	2.7
		Maple	536	68	12.7	133	1.4
		Oak	563	58	10.3	87	0.9
		Other species	1734	263	15.2	453	4.8
		Yellow-poplar	889	123	13.8	218	2.3
	Intermediate	Black cherry	79	13	16.5	34	0.4
		Maple	1688	127	7.5	222	2.4
		Oak	267	14	5.2	19	0.2
		Other species	2249	216	9.6	407	4.3
		Yellow-poplar	213	16	7.5	26	0.3
	Suppressed	Black cherry	14	6	42.9	13	0.1
		Maple	2690	120	4.5	239	2.5
		Oak	59	6	10.2	6	0.1
		Other species	2371	146	6.2	273	2.9
		Yellow-poplar	90	2	2.2	4	0.0
	TOTALS	Black cherry	4351	1289	29.6	1861	19.8
		Maple	21504	1303	6.1	1833	19.5
		Oak	6435	646	10.0	799	8.5
		Other species	33050	2696	8.2	3899	41.4
		Yellow-poplar	5649	718	12.7	1022	10.9
		Sum	70989	6652	9.4	9414	100.0

control plots, likely indicating that grapevine density in treated plots increased from 1986 to 2004, while grapevine density decreased in the control plots during the same years. Crawford (1971) and Trimble and Tryon (1974, 1979) noted that vines originating from sprouts grow faster and more vigorously than vines originating from seeds, and vigorous sprouting might explain the limited effectiveness of treatments. Beck and Hooper (1986) also observed moderate success in controlling grapevine densities in young stands 5 years following treatment. Success of the control treatment applied on the HNF appears limited.

Other than reports of stem breakage and other quality issues related to entanglement with grapevines, no research has reported loss of growth or effects on species composition. Based on our results looking at individual trees with vines, grapevines do not appear to randomly disperse among the available species. Thirty percent of all vines were found in black cherry, while black cherry comprised only about 17 percent of all trees (Table 4). On the other hand, oak species, which outnumber the black cherry stems, had about half the total number of stems with vines. Differences in numbers of vines observed may be attributed to the finer, more numerous branches of black cherry, as well as to an association between the period of fruit ripening of both species and similar browsers using the fruits as a food source.

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THINNING RESULTS FROM A MIXED UPLAND HARDWOOD STAND AFTER 35 YEARS

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Abstract.—A long-term study of precommercial thinning was installed in a 6-year-old oak-dominated stand regenerated by clearcutting in the southern Appalachian Mountains of North Carolina. Three levels of residual stand density were tested: control (no thinning), and 200, and 400 residual trees per acre (TPA). Objectives of the study were to determine the response of an upland hardwood stand to thinning based on diameter at breast height (d.b.h.) and basal area increment. Analyses indicated that mean d.b.h. for the 200 TPA thinning treatment was significantly larger at 11, 24, and 35 years after thinning. There were no significant differences in mean total basal area per acre between all treatments in any period, with the exception of 11 years after thinning, when control plots had significantly lower basal area. The 200 TPA thinning treatment did increase total basal area of the drier-site oaks that remained competitive. Results of this study suggest that young mixed-oak stands on low to intermediate quality sites respond in diameter growth to a single precommercial thinning treatment early in the stem exclusion stage of stand development where stand density is reduced to 200 or fewer trees per acre.

INTRODUCTION

Many mixed upland hardwood forest stands on low quality sites in the southern Appalachians have been cut over and are understocked, but well stocked stands have originated from one or more clearcuttings (Schnur 1937). A number of options are available for management of such fully stocked young stands (Gingrich 1971a), particularly thinning treatments (Dale 1968, Hilt 1979, Hilt 1982). Management decisions for the enhancement of timber production and wildlife habitat are important for landowners with low to moderate quality forest sites in the southern Appalachians. Marginal productivity and low quality of timber products cause forest managers to consider early stand treatments that will reduce competition for site resources and concentrate growth on potential crop trees.

OBJECTIVES

A study of precommercial thinning was initiated in the spring of 1971. Boyette and Brenneman (1978) reported results after 5 years. At the time this study was initiated, very little information on precommercial thinning effects in upland hardwood stands that are predominately oak was available. Guidelines for appropriate thinning treatments were difficult to establish for early stand development because of several factors that can influence release responses, such as species, thinning density, type of release, spacing, and species-site interactions (Hilt and Dale 1987).

The primary objective of the study was to examine response to precommercial thinning treatments in a recently regenerated oak-dominated stand on a low to intermediate quality site. This report presents results of that study based on data collected at 16, 30, and 41 years after harvest.

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STUDY AREA

The study site is in the Bent Creek Experimental Forest, about 10 miles south of Asheville, NC. Situated in the Blue Ridge Physiographic Province, Bent Creek is a 6,000-acre drainage basin that receives about 45 inches of precipitation annually. The study site is in the lower end of the basin, on an intermountain area of low relief and Piedmont-like terrain. Elevation at the study site is 2,200 feet. The area occupies the mid to lower portion of a long, south-facing slope. Soils are mostly a complex of eroded Evard-Cowee loams, a common series on broad ridges and relatively level areas of intermountain basins. The complex Typic Hapludults with solum depths greater than 40 inches, is relatively low in productivity with a site index (SI_{50}) of 65-70 feet base age 50 for upland oaks.

METHODS

This study was installed in a 6-year-old stand of stump sprouts and advance regeneration that originated from clearcutting a predominantly shortleaf pine (*Pinus echinata* Mill.) stand with a midstory of mixed hardwoods. The hardwood component consisted mainly of oaks (*Quercus* spp): scarlet (*Q. coccinea* Muenchh.), black (*Q. velutina* Lam.), white (*Q. alba* L.), chestnut (*Q. prinus* L.), southern red (*Q. falcata* Michx.), northern red (*Q. rubra* L.), and post (*Q. stellata* Wangenh.). Other hardwoods included red maple (*Acer rubrum* L.), yellow-poplar (*Liriodendron tulipifera* L.), and sourwood (*Oxydendrum arboreum* (L.) DC.). Scattered groups of white pine (*Pinus strobus* L.) had been planted before the previous timber stand was harvested. Site preparation consisted of clean felling residual stems greater than 4.5 feet in height. The young stand of natural regeneration was severely overstocked for optimum timber production.

Four replicates of two precommercial thinning treatments were installed and compared to a no thinning control. Study treatments consisted of: 1) thinning to 400 trees per acre (TPA); 2) thinning to 800 TPA; and 3) a control plot in which no thinning was done. Treatment plots were 0.25-acre in area with a 0.10-acre center measurement plot. Crop trees were selected based on criterion of species, uniformity of spacing, tree quality, and the potential to develop into sawtimber. The preferred crop tree species selected for release were drier-site oaks, then mesic-site oaks, and yellow-poplar. This procedure resulted in the selection of some intermediate and suppressed trees being selected as crop trees, especially in the 800-TPA treatment and the control plots.

Measurement trees in each plot were identified by tree number and followed over several measurement periods, which allowed for survival and growth of individual trees to be followed. The initial stem height measurements were made in early spring 1972, immediately following the installation of the precommercial thinning treatments. All crop trees were measured in the treated plots. Repeat measurements of height and d.b.h. of the selected crop trees were made in the spring of 1977, 1982, 1996, and 2007, at stand ages 11, 16, 30, and 41 respectively.

In 1977, 5 years following the initial precommercial thinning treatments, the 800 TPA treatment was modified. It was determined that thinning to 800-TPA was not severe enough to provide adequate growth response in comparison with the control or 400-TPA treatment. To determine if heavier thinnings were beneficial, the 800-TPA treatment was thinned to 200 TPA. The final thinning treatments were: 1) thinning to 400 TPA at age 6; (2) thinning to 800 TPA at age 6 and 5 years later thinning to 200 TPA; and (3) a control plot in which no thinning was done.

Table 1.—Stand density (TPA), total basal area (ft^2/acre), mean d.b.h. (inches), and percent stocking levels by thinning treatment, stand age, and assessment year

	1982 Stand Age 16			1996 Stand Age 30			2007 Stand Age 41		
	Control	200	400	Control	200	400	Control	200	400
Trees per acre	417	209	415	242	179	223	233	177	205
Total basal area	18	24	34	92	64	71	130	95	100
Mean d.b.h.	2.5	4.5	3.5	7.9	8.5	7.4	8.9	10.5	8.4
Percent stocking level	<30	<30	40	85	58	68	110	80	90

Analysis of variance was used to identify significant differences (probability level $P < 0.05$) among thinning treatments. Response variables included mean d.b.h. (inches), basal area (feet^2 per acre), and TPA for each precommercial thinning treatment at the time of each measurement. SAS 9.1.3 Service Pack 3 General Linear Models Procedure was used for all statistical analyses (SAS Institute Inc. 2004).

RESULTS

Stand Density and Development

Between 1982 and 1996, the natural mortality in the unthinned control treatment was 42 percent, with stand density decreasing from 417 to 242 TPA (Table 1). The mortality in the 400 TPA thinning treatment was similar at 47 percent, decreasing from 415 to 223 TPA. During this same period, natural mortality in the 200 TPA thinning treatment was 14 percent, decreasing from 209 to 179 TPA.

On average the TPA remained constant for the three treatments during the period 1996 to 2007, while the mean d.b.h. growth has slowed down considerably from the previous period. Stand conditions were moving into fully stocked conditions with stocking levels of 58, 68, and 85 percent for the 200 TPA, 400 TPA, and unthinned control treatments, respectively, at stand age 30.

By the 2007 assessment (age 41 years), stand conditions have reached stocking levels of 80, 91, and 110 percent for the 200-TPA, 400-TPA, and unthinned control treatments, respectively (Table 1). The unthinned control treatment was at the overstocked stocking level prior to mid rotation and trees reaching small sawtimber size.

Mean d.b.h. Development

Mean d.b.h. for the 200-TPA thinning treatment was significantly larger than the 400-TPA thinning treatment and the unthinned control at each sample period (Table 2). Despite different mean diameters at age 16 between the 400-TPA thinning treatment and the unthinned control, there were no differences in mean d.b.h. between these two treatments as the stand matured between age 30 and age 41.

Differences were not detected when only dominant and codominant crop trees were assessed (data not shown). The mean d.b.h. growth increases were largest for the period between 1982 and 1996. Trends indicate that white pine grew to the largest mean diameters across all thinning treatments, followed by scarlet oak, yellow-poplar, chestnut oak, and white oak. Except for chestnut oak, mean d.b.h. for all other species was largest in the 200-TPA thinning treatment when compared to the 400-TPA and the unthinned control (Table 3).

Table 2.—Mean d.b.h.(inches) by thinning treatment and assessment year

Thinning Treatment	1982 Stand age 16	1996 Stand age 30	2007 Stand age 41
Unthinned control	2.5 c	7.9 b	8.9 b
200 TPA thin	4.5 a	8.5 a	10.5 a
400 TPA thin	3.5 b	7.4 b	8.4 b
R^2	92	95	95

*Values with the same letter within the same measurement period are not significantly different at the P <0.05

Table 3.—Mean d.b.h. (inches) for selected species by thinning treatment, stand age, and assessment year

Species	1982 Stand age 16			1996 Stand age 30			2007 Stand age 41		
	Control	200	400	Control	200	400	Control	200	400
Yellow-poplar	3.1	4.5	3.9	7.9	8.0	7.5	9.7	10.5	9.1
Scarlet oak	2.1	4.7	3.6	6.5	8.4	8.0	7.9	10.9	9.8
Black oak	2.0	3.9	2.5	5.2	7.2	5.9	6.9	8.7	7.0
White oak	2.7	4.7	4.1	6.0	7.7	7.1	6.6	8.7	8.2
Chestnut oak	3.7	4.8	4.6	7.6	7.8	8.1	9.9	9.9	10.1
White pine	3.6	8.0	7.6	13.0	19.6*	14.3	15.4	23.2*	17.8

* d.b.h. from a single tree in thinning treatment

Table 4.—Mean annual basal area growth rate (ft^2) and mean annual d.b.h. growth rate (inches) by thinning treatment from 1996-2007 (age 30 to 41 years)

Thinning Treatment	Mean annual basal area growth rate from 1996-2007 (age 30 to 41)	Mean annual d.b.h. growth rate from 1996-2007 (age 30 to 41)
Unthinned control	3.6 a	0.14 b
200 TPA thin	2.9 a	0.16 a
400 TPA thin	2.9 a	0.13 b
R^2	85	86

*Values with the same letter within the same measurement period are not significantly different at the P <0.05.

The mean annual d.b.h. growth rate for the 400-TPA thinning treatment was not significantly different from the unthinned control treatment (Table 4). The mean d.b.h. growth rate for the 200-TPA thinning treatment was significantly larger than the unthinned control and the 400 TPA treatment. This range of mean annual d.b.h. growth rate (0.13 to 0.16 inches) for these thinning treatments was similar to other thinned even-aged upland oak stands between ages 30 and 40 years with stocking levels between 45 and 65 percent (Gingrich 1971b).

Total Basal Area Development

In 1982, the thinning treatments resulted in significantly higher total basal area than the unthinned control treatment (Table 5). The total basal area per acre in the 400-TPA thinning treatment was almost double

Table 5.—Total basal area (ft^2/acre) by thinning treatment, stand age, and assessment year

Thinning Treatment	1982 Stand Age 16	1996 Stand Age 30	2007 Stand Age 41
Unthinned Control	18 b	92 a	130 a
200 TPA Thin	24 a	64 a	95 a
400 TPA Thin	34 a	71 a	100 a
R^2	86	88	87

*Values with the same letter within the same measurement period are not significantly different at the P <0.05

that of the control. By stand age 30 and through age 41, no significant differences in total basal area per acre for any of the treatments remained. This finding was also true when only dominant and codominant crop trees were assessed.

No significant differences in mean annual basal area growth rate were found between any of the thinning treatments and the unthinned control for the period between stand ages 30 and 41 years old (Table 4). The 2.9 mean annual basal area growth rate for both thinning treatments is similar to other even-aged upland oak stands at stand age 30 years with 50 to 60 percent stocking (Gingrich 1971b). The larger mean annual growth rate for the unthinned control was due to a larger number of trees of a smaller average diameter.

As the stand developed following thinning treatments, the drier-site upland oak species, including white oak, scarlet oak, and black oak, comprised more of the total basal area per acre in both the 200 TPA and 400 TPA treatments, when compared to the unthinned control (Table 6). Chestnut oak also comprised a large part of the total basal area per acre in both the 400 TPA and unthinned control treatments. The 200-TPA thinning treatment did increase the amount of total basal area of white oak, black oak, and scarlet oak that remained competitive at stand ages 30 and 41. Species such as black cherry, northern red oak, southern red oak, and post oak responded poorly during this stage and were overtopped by the drier-site oaks, yellow-poplar, and white pine. By stand age 30, the northern red oak and post oak had dropped out of all the treatments (Table 6). Red maple ingrowth has also increased in the unthinned control and 400-TPA thinning treatment.

By stand age 30, white pine trees that were present or seeded in naturally underneath the open hardwood canopies following disturbance comprised a greater percent of the total basal area per acre in the unthinned control treatments because they were not thinned out (Table 7). In the unthinned control white pine increased from 3 to 45 percent of the total basal area between stand ages 16 and age 30 at the expense of drier-site oak species and yellow-poplar. The percent of total basal area per acre for these drier site oak species during this period was greater in the 200 -PA and 400-TPA thinning treatments when compared to the unthinned control (Table 7).

DISCUSSION

Five years following the precommercial thinning treatments (1977 assessment; stand age 11), mean d.b.h. was significantly larger for the 400-TPA thinning treatment when compared to the other treatments while the mean d.b.h. for the 800-TPA thinning treatment was not significantly different from the unthinned control (Boyette and Brenneman 1978). Thinning to 800 TPA did not provide a sufficient tree growth response to justify future recommendations in young upland hardwood stands.

Table 6.—Total basal area (ft^2/acre) by species, thinning treatment, and assessment year

Species	1982 Stand Age 16			1996 Stand Age 30			2007 Stand Age 41		
	Control	200	400	Control	200	400	Control	200	400
Yellow-poplar	4.7	2.9	4.6	14.6	6.6	7.0	22.2	11.2	10.4
Scarlet oak	2.4	4.8	4.8	6.2	14.1	13.0	8.3	22.2	17.1
Black oak	2.2	3.0	4.9	4.1	8.7	7.6	6.9	13.2	8.2
White oak	3.5	7.9	5.8	5.6	20.1	9.5	6.6	26.3	12.8
Chestnut oak	2.5	3.0	7.6	13.3	9.5	18.6	21.2	15.1	28.0
White pine	0.6	0.9	3.1	42.0	5.2*	11.2	58.1	7.3*	17.4
Hickory	0.5	0.1	1.1			0.1			0.2
Red maple				2.3		2.8	3.0		4.3
S. red oak	0.3	0.3	0.6			1.0			1.6
Black cherry	1.0	0.3	0.3	1.2			1.2		
N. red oak	0.2	0.2	0.7						
Post oak		0.2	0.2						
Other	0.2	0.1	<0.1	2.4			2.7		
Total basal area per acre	18	24	34	92	64	71	130	95	100

*Basal area from a single tree in thinning treatment

Table 7.—Percent of total basal area per acre for drier site oaks, yellow-poplar, and white pine by thinning treatment and assessment year

Species	1982 Stand age 16			1996 Stand age 30			2007 Stand age 41		
	Control	200	400	Control	200	400	Control	200	400
Drier site oaks	59	78	67	32	82	68	33	80	66
Yellow-poplar	26	12	14	16	10	10	17	12	10
White pine	3	4	9	45	8	16	45	8	17

Results from this study show that any increase in tree growth for the 400-TPA thinning treatment became less significant with later stand development. Another follow-up thinning may have been beneficial before stand age 30, although the stocking level was 68 percent and still considered adequate for stand growth. Gingrich (1971b) found that a single thinning, unless followed by a series of thinnings at 10- to 15-year intervals, is of doubtful value. A 400-TPA precommercial thinnning level may be more appropriate if applied later in the stem exclusion stage of stand development and followed up with subsequent thinnings.

On this site, precommercial thinning to the lower 200-TPA density levels at stand age 11 resulted in increased diameter growth that was maintained after 35 years. The 200-TPA thinning treatment was at the 58 percent stocking level at stand age 30. The 200-TPA thinning treatment was at the B-line stocking level considered to be optimal stocking for additional stand growth (Gingrich 1971a).

Precommercial thinning did help to remove unmerchantable stems which upgraded the quality and growth potential of the residual stand while improving species composition. Results indicate that the species mixture of more desirable oak species was improved by precommercial thinning and increased the percentage of total basal area per acre in thinned treatments when compared to the unthinned control. Thinning also helped to reduce the density of white pine trees that were present in the species mixture, allowing for more hardwood development. In the unthinned control, white pine ingrowth has created more of a conifer-hardwood mixed stand dominated by pines. This ingrowth of white pine trees in the unthinned control may have also contributed to reduced treatment differences between hardwood trees that were precommercially thinned.

Without some type of thinning on these drier sites, natural white pine stems may inhibit the early growth and development of desired oak species. On these drier sites in the southern Appalachian mountain region, previous researchers have found that white pine will out-compete most other species regardless of site quality, except yellow-poplar on SI_{50} >95 feet (Doolittle 1958).

Where landowners want to produce both timber value and wildlife benefits, white pine can be an acceptable species to grow in mixtures on these drier sites. However, careful consideration should be given to how many white pine and yellow-poplar trees to leave when grown in mixtures on dry sites naturally regenerating to oak. These species, if not reduced to lower densities, can overwhelm young oak stands at higher stocking levels (Beck and Hooper 1986). Although yellow-poplar grew well from stump sprouts, management of this species is generally not recommended on sites of low to intermediate quality (Beck and Della-Bianca 1981).

For this study, the initial thinning treatment at age 6 was applied too early in the stem initiation stage of stand development. Other researchers have found that growth responses have been inconsistent for released crop trees in young stands less than 10 years after clearcutting (Hilt and Dale 1982, Trimble 1971). On these drier sites, precommercial thinning should be delayed until the stand reaches between 15 and 20 years old. Younger hardwood trees would respond better following more time for crown development. By waiting for the stand to develop further, foresters can better select the highest quality dominant trees of the preferred species. Landowners and foresters should plan their selection of crop trees and species composition based on which species are best adapted to their sites for the length of the rotation. A mixed species stand is very suitable for sites with SI_{50} less than 70 feet for upland oak where both timber and wildlife values are desirable.

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STAND DEVELOPMENT OF TREMBLING ASPEN IN CANAAN VALLEY, WEST VIRGINIA

James S. Rentch and James T. Anderson[1]

Abstract.—In wetlands of Canaan Valley, West Virginia, trembling aspen occurs as a disjunct population well south of its primary natural range. Based on sample data from 15 stands, we found that aspen occurs as nearly monospecific stands or clones. Eight stands had median ages between 30 and 40 yrs, and we suggest that stand initiation was related to changes in land use after the 1950s. Nine stands were in the stem exclusion stage of development, with mortality concentrated in smaller aspen stems. Five stands showed evidence of overstory mortality and expansion at the stand boundary, based on a comparison of ages of the largest and smallest trees along a distance gradient from stand center to edge. We suggest that the lack of stronger evidence of stand expansion can be attributed to competition from adjacent plant communities, and the presence of unfavorable soil and/or hydrologic conditions necessary for successful aspen ramet emergence and survival.

INTRODUCTION

Trembling aspen (*Populus tremuloides* Michx.) is the most widely distributed native tree species in North America (Perala 1990). The species grows singly and in multi-stemmed clones, and often depends on fire for establishment. During the past 50 years, a major land management controversy has developed in North America over the extent to which altered fire regimes, increasing ungulate populations, and climate change have or have not resulted in declines in aspen abundance, vigor, or regeneration (Hessl 2002, Kaye and others 2003, Kashian and others 2007). In western settings, researchers have emphasized the need to apply appropriate spatial and temporal scales to assess aspen condition (Turner and others 2003, Kashian and others 2007). In West Virginia, a disjunct population of trembling aspen occurs approximately 100 km south of its primary range (Perala 1990) in the 30-km^2 wetland areas of Canaan Valley. Although trembling aspen occurs elsewhere in the state, climatic conditions in Canaan Valley closely resemble boreal conditions to the north, and aspen assumes a clonal growth form that is readily observable.

In its primary range, aspen has high commercial value. In Canaan Valley, wildlife, biodiversity, and aesthetic values are more important. Aspen stands provide habitat for several plant species of concern, including *Viburnum lentago* (state rank S2, "rare and imperiled," West Virginia Natural Heritage Program 1995), *Equisetum sylvaticum* (S1, "extremely rare and critical imperiled") and *Polemonium vanbruntiae* (S2). Aspen stands are also an important food source for beaver (*Castor canadensis*), and habitat for a wide variety of breeding birds and other wildlife needing young forests, particularly woodcock (*Scolopas minor*)(Kletzly 1976). Canaan Valley has historically contained the best habitat and highest woodcock populations in the state (Webb and Samuel 1982, Steketee 2000), and the area is an important migration staging area for the species (U.S. Fish and Wildlife Service 1990). Habitat loss is thought to be a primary factor contributing to woodcock population declines in the state (Bruggink 1997) and elsewhere.

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OBJECTIVES

Because of wildlife and biodiversity concerns, wildlife managers are interested in sustainable management and thus the population dynamics of these disjunct aspen stands. The purpose of this study was to evaluate the composition and structure of trembling aspen stands in Canaan Valley National Wildlife Refuge (CVNWR) in Tucker County, WV. Specifically, we assessed tree diameter and age structures and distributions, patterns of stand initiation, stem mortality, and species replacement. As part of a final objective, we determined whether the CVNWR aspen stands tend to expand or whether they are relatively static in size.

STUDY AREA AND METHODS

Canaan Valley is an elongated, eroded valley in Tucker County, WV, in the Allegheny Mountain Section of the Appalachian Plateau Physiographic Province (Fennerman 1939). The diverse assemblage of bogs, fens, wet meadows, and swamps in the valley totals nearly 3,000 ha (Fortney and Rentch 2003). Aspen occurs on poorly drained, mottled, silt or clay loams, underlain by clay or clay loams, including those of the Blago (Typic Umbraquults), Brinkerton (Typic Fragiaqualfs), and Lickdale (Haplaquepts) series (Fortney 1975, Nat. Resour. Conserv. Serv. 1995). Organic soils are largely absent, and hydric soil indicators include depleted matrix and redox depressions (Byers and others 2007).

The average freeze-free period in Canaan Valley is 90 days (Beverage 1967), and frost may occur during any month. Mean January and July temperatures are -3.5 °C and 18.7 °C, respectively. Mean annual precipitation is 127.2 cm (Natl. Climate Data Center 2003). A distinguishing climatic feature of Canaan Valley is a frost pocket effect: the drainage of cold, nocturnal air downslope into concave land formations, depressing temperatures on the valley floor.

One notable feature of aspen in Canaan Valley is that the species is more abundant now than in the prelogging environment. Accounts of prelogging vegetation (e.g., Brooks 1911, Clarkson 1993) suggest that the primary vegetative cover on the valley floor was a mixed spruce-hemlock swamp forest with an understory of *Rhododendron maximum* L. During the railroad logging era of 1886-1924, forests were clearcut and slash and exposed soils were subject to extreme drying. As a result, much of the valley burned repeatedly from ignitions from logging operations. Following burning, the plant environment became more favorable to aspen, primarily by the exposure of mineral soil, critical for aspen germination (Barnes 1966, Perala 1990), and the reduction of seed source of red spruce and other woody competitors.

Trembling aspen stands were identified from 1997 National Aerial Photography Program imagery (Fortney and Rentch 2003). Using ArcView 3.2 (Environmental Systems Research Inc., Redlands, CA), we identified aspen stands based on the vegetation signatures of the 1997 imagery and ground truthing activities. This shape file was then overlaid on an orthorectified 1945 U.S. Department of Agriculture black and white panchromatic print and modified based on vegetation signatures. From forest cover classification, we estimated descriptive statistics in the valley for the two time periods. Because the distribution of aspen polygon size was heavily skewed toward smaller stands (skewness = 8.7 and 6.0 for 1945 and 1997 data, respectively), we used median as the measure of central tendency.

We then selected 14 stands in the field that were representative of a broad range of age and size classes from several different areas of the valley. In each stand, a 20 x 25 m permanent plot was established in the center. Additional data from one 400 m^2 sample plot were provided by WV Division of Natural Resources. In each plot, we conducted a 100 percent tally for saplings (diameter at breast height [d.b.h.] <2.5 cm, height >1 m) and live and standing dead trees (d.b.h. ≥2.5 cm).

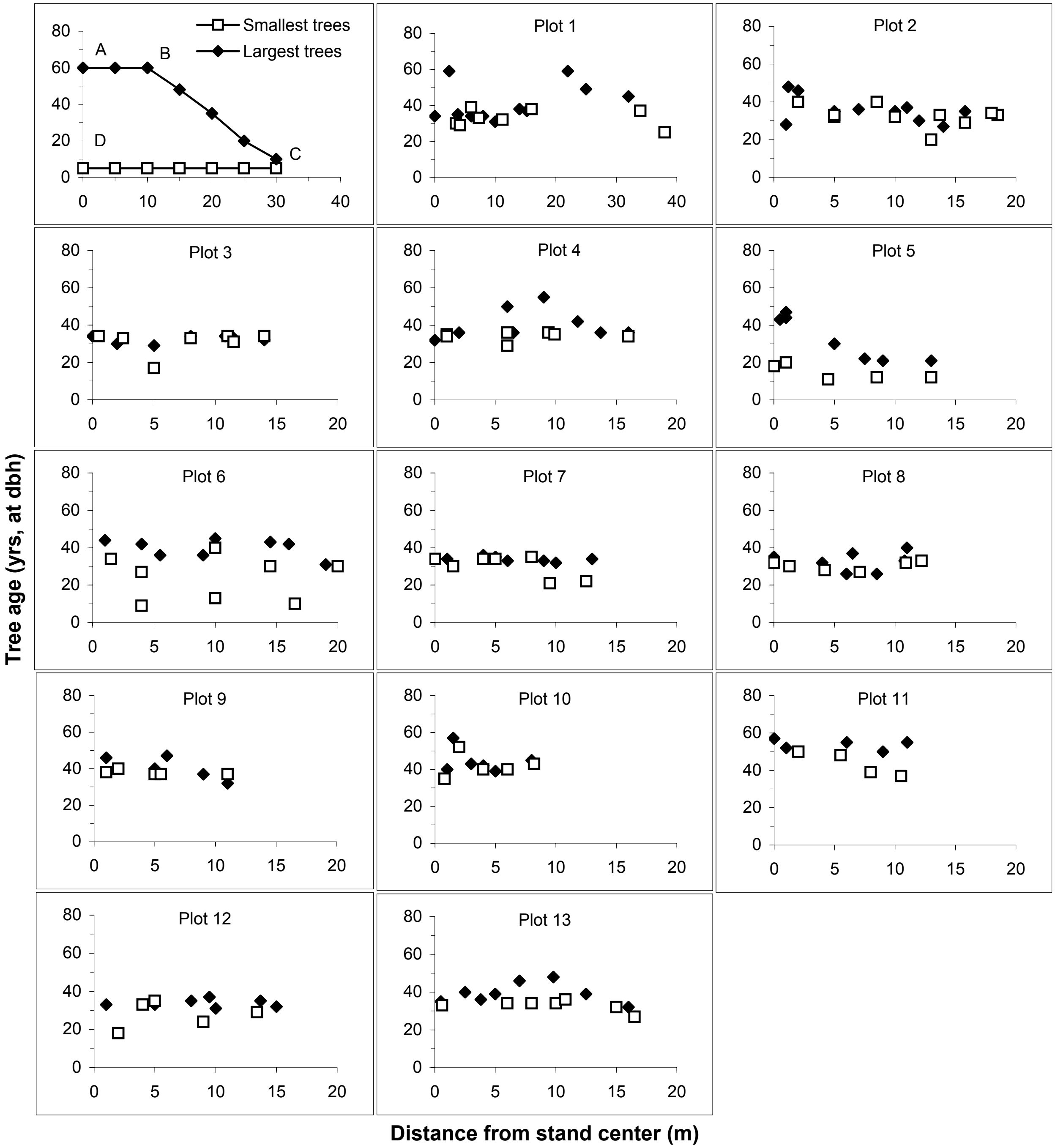

Figure 1.—Scattergrams of trembling aspen age at d.b.h. (yrs) and distance (m) from stand center along two distance gradients, Canaan Valley National Wildlife Refuge, Tucker County, WV. Large trees are diamonds, small trees are squares. Theoretical model, based on Leak and Graber (1976), is shown in first panel.

We adapted a method proposed by Leak and Graber (1974) that uses age structure to determine rate of stand expansion. They proposed that a change in stand boundary should be reflected in the relationship between maximum and minimum stem age over a distance gradient from the center of a stand to its edge (Leak and Graber 1974, Solomon and Leak 1994). When a stand first initiates, line AB of Figure 1 represents the theoretical model of age distribution of the largest trees. Advanced regeneration within the stand is represented by line DC, and recruitment at the stand edge and boundary advance is represented by line BC.

Using this technique, we established two random transects from the stand center to the outer edge, and we took increment cores or cross-sections (at breast height, 1.7 m) from both the largest and smallest aspen stems at regular intervals (i.e., every 3-5 m, depending on stand size and transect length) to the outer edge. Mean transect length from center to edge was 15.0 m (± 1.4). Age data were collected for 189 trees but not collected for plots 14 and 15. We prepared and cross-dated samples using standard dendrochronological techniques, and measured annual rings under a dissecting microscope to the nearest 0.001 mm. Tree-ring dating was validated using the program COFECHA (Holmes 1983). Aspen age distributions refer to minimum time since stand initiation, not true clonal age, which is very difficult to determine (Kashian and others 2007). In addition, tree ages do not include an estimate of the number of years required to reach breast height.

RESULTS

Valley-wide Trends 1945-2000

Landscape-level statistics for 1945 and 1997 were of the same order of magnitude for median stand size, total area, and total number of stands (Table 1). Results for the two time periods differed primarily in maximum stand size. In 1945, the largest stand was 0.85 ha, while in 1997 the largest stand was 9.8 ha, and three areas were >5 ha in size. Estimates of median stand size are slightly larger than values in the literature cited for eastern aspen (e.g., Kemperman and Barnes 1976, Peterson and Squiers 1995), which we attribute to the difficulty of using GIS to identify and map very small stands of only a few trees.

Table 1.—Descriptive statistics for trembling aspen stands in Canaan Valley, Tucker County, WV, 1945-1997, from interpretation of aerial photographs.

Parameter	1945	1997
Median size (ha)	0.06	0.10
Minimum size (ha)	0.02	<0.01
Maximum size (ha)	0.85	9.83
Total area (ha)	43	61
Count	148	142

Stand composition and structure

At minimum, aspen constituted 96 percent of the total basal area and 88 percent of the total sampled trees (Table 2). The only non-aspen overstory species present was red spruce (*Picea rubens* Sarg.), which occurred once in each of two plots. Understory tree species present but not abundant were hawthorne (*Crataegus* sp.) and serviceberry (*Ameliancher laevis* Wieg) and no aspen saplings were tallied in four plots (4, 10, 11, 14). Shrub cover averaged 26.5 percent (SE = 5.0 percent), primarily *Vaccinium myrtilloides* Du Roi and *Spiraea alba* Michaux. For all but two sample plots, the distribution of live and dead trees tended to approximate normality (Fig. 2), although positively skewed with a heavy right tail (Krasny and Johnson 1992). Based on age distributions, eight stands (plots 3, 7, 8, 9, 11, 12, 13) were in the stem exclusion stage (Oliver and Larson 1996) and the remaining stands were in understory reinitiation, indicated by the presence of younger cohort(s). Quadratic mean diameter (QMD) of standing snags in two URI stands (plots 5, 10) was >QMD of live stems; for these and two additional stands, the ratio of dead:live basal area >0.28, which met the criteria for the onset of stand breakup as proposed by Pothier and others (2004).

Median age for 10 stands was between 30 and 40 yr, with relatively tight age distributions around the median and a range of ≤8 yr between the 25th and 75th percentile, suggesting either that little mortality of the initial cohort had occurred, or that stand expansion was in its relatively early stages. Similarly, for 10 stands, the difference between the median age for large and small trees was ≤5 yr (Table 3).

Stand/Clone Expansion

For most stands (plots 2, 3, 6, 7, 8, 9, 11, 12, 13), the ages of smallest and largest trees along the distance gradient from center to edge were very similar, and no or only slight changes in stem age across the outer

Table 2.—Density (TPH, trees/ha; BAH, basal area/ha, m²), and quadratic mean diameter (QMD, cm) for live and dead saplings (d.b.h. < 2.5 cm, height > 1 m) and trees (d.b.h. > 2.5 cm) from 15 trembling aspen stands, Canaan Valley National Wildlife Refuge, Tucker County, WV. Ratio is the ratio of dead BAH to live BAH. "Other" includes red spruce, hawthorns, and serviceberry.

	Live aspen			Dead aspen			Ratio	Other		
Plot	TPH	BAH	QMD	TPH	BAH	QMD	D/LBa	TPH	BAH	QMD
1	1100	23.0	16.3	360	6.7	13.8	0.29	150	0.5	6.2
2	1680	26.0	14.0	280	2.6	10.8	0.10	-	-	-
3	1340	25.0	15.4	440	6.7	13.9	0.27	20	0.1	5.5
4	1500	26.1	14.9	500	3.8	10.0	0.15	-	-	-
5	4600	18.9	7.2	920	5.3	8.5	0.28	-	-	-
6	2200	21.8	11.2	1060	7.2	9.3	0.32	-	-	-
7	2400	30.0	12.6	600	4.7	10.0	0.16	-	-	-
8	2020	26.8	13.0	1040	4.6	7.5	0.17	-	-	-
9	2600	22.9	10.6	440	1.5	6.6	0.07	-	-	-
10	1020	28.2	18.8	360	11.3	20.0	0.40	120	0.3	5.2
11	1200	32.2	18.5	360	4.0	11.9	0.12	-	-	-
12	2700	15.9	8.7	500	1.8	6.8	0.11	20	0.1	5.6
13	1620	19.3	12.3	420	1.4	6.6	0.07	-	-	-
14	1020	5.6	8.3	na	na	na	na	20	0.1	5.6
15	1275	18.5	13.4	225	2.1	18.9	0.11	25	0.6	17

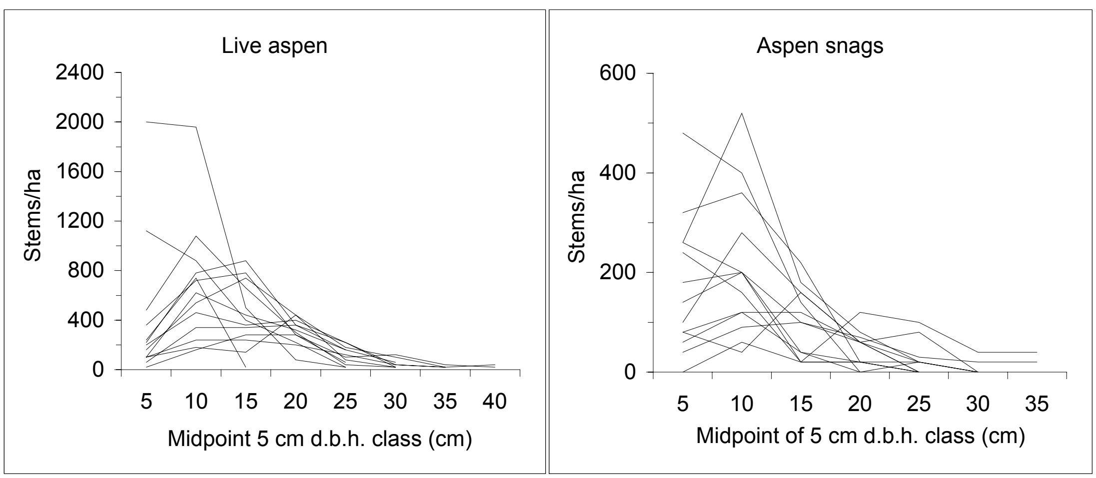

Figure 2.—D.b.h distribution (stems/ha) of live aspen and standing aspen snags (d.b.h. >2.5 cm) for 15 sample stands, Canaan Valley National Wildlife Refuge, Tucker County, WV.

stand boundaries were observed (Fig. 1). For the four remaining stands there was a general trend of decreasing stem age at the stand edge, although only stand 5 closely approximated the model of Figure 1.

Age distributions of several plots (1, 4, 5, 6) also suggest that scattered overstory mortality and replacement have occurred. In these plots, diameter differences reflect different times of establishment. For example, the oldest cored tree in plot 1 (Figure 1) occurred 22 m from stand center, and tree age declined from there to stand edge at 38 m. Toward the center of this plot, tree ages ranged from 31 to 59 yr. Based on the ages of the oldest and youngest trees, the earliest overstory stem mortality/replacement occurred between stand-ages of 20 and 30 yr.

Table 3.—Median tree ages for largest and smallest trees along transects from center to edge of stand, for 13 trembling aspen plots, Canaan Valley National Wildlife Refuge, Tucker County, WV.

	Median Age (yrs)	
	Largest trees	Smallest trees
Plot 1	37	32
Plot 2	35	33
Plot 3	33	33
Plot 4	36	35
Plot 5	30	12
Plot 6	42	28
Plot 7	34	34
Plot 8	34	na
Plot 9	40	37
Plot 10	42	40
Plot 11	55	44
Plot 12	33	29
Plot 13	39	34

DISCUSSION

Aspen stands in Canaan Valley have been a feature of the landscape since exploitative harvesting ceased during the late 1920s. Between 1945 and 1997, little change in the number of stands, total area, or median size was found. We suggest that the initiation of aspen in the study area was linked to land-use changes following harvest. Beginning in the early 1940s, many of the better drained lowland areas that are now aspen stands were converted into agricultural land. Large areas were sown in grass for pasture and hay, and hundreds of head of stock grazed. Tillable areas also were converted to row crops, including potatoes and cauliflower (Fortney 1993). Row-crop agriculture was largely abandoned in the 1950s, and the last of the grazing horses and cattle were removed during the 1960s (Michael 2002).

Stand median ages are synchronous with this chronology. Stands initiated between 30 and 55 yr ago, and we propose that the oldest stems of aspen were from seedlings that initiated after the forests were first harvested and burned. Younger trees may have been ramets of these pioneer seedling-origin trees—suckers that initiated after some type of disturbance or overstory mortality—and the youngest stems were probably second-generation ramets of the seedling-initiated stems.

Ages of the largest and smallest trees from center to edge were relatively uniform for more than two-thirds of the stands, indicating that all stems generated more or less simultaneously, and that stands were in the stem exclusion stage of development. Conversely, the remaining stands showed evidence of overstory mortality and the initiation of new stems from center to edge, as well as an advancing edge. The onset of overstory mortality and establishment within the stand and along its edge does not appear to be simply age-related, since there were few overall differences in median stand age between those that were stationary and those that were expanding. Peterson and Squiers (1995) noted that stand boundaries may be relatively fixed because of competition from adjacent plant communities. In Canaan Valley, the juxtaposition of some aspen stands with *Sphagnum* and *Polytrichum* bogs, shrub thickets, and sedge clones (*Carex* sp.) may provide conditions that resist encroachment by aspen suckers. Hogg and Lieffers (1991) found that vigorous competitors such as bluejoint grass (*Calamagrostis canadensis* Michx.) can significantly reduce sucker growth. Fortney (1975) found aspen stands in Canaan Valley that were established in *Polytrichium* bogs, but these stands tended to be of low vigor, and short-lived due to nutrient shortages, competition, and cold-injury.

The presence of unfavorable soil conditions within and at the stand boundary also may discourage ramet emergence and/or survival, and may hasten overstory mortality. Aspen growth tends to be reduced on finely textured soils with hardpans that restrict rooting depth (Stoeckler 1960), and flooding or saturation after disturbance inhibits root suckering (Frey and others 2003). Even in cases of high soil moisture, low oxygen availability may inhibit water uptake and create conditions of moisture stress, leading to poor vigor, reduced growth, and mortality (Frey and others 2004). In Canaan Valley, soil and hydrologic complexity on the valley floor may limit growth and regeneration and provide unseen obstacles to clonal expansion.

Finally, due to the clonal nature of aspen, stem growth, mortality, and ramet emergence are all group phenomena (Frey and others 2004). Therefore, observed differences in stand development may be, in part, attributable to genetic variability among clones and across the Canaan Valley population. These effects may be distinct from restrictions on growth and regeneration imposed by environmental variability of soils, soil moisture, and composition of adjacent plant communities.

In contrast to stand development patterns in other regions, where trembling aspen is often replaced by more shade-tolerant species (Bates and others 1989, Perala 1990, Peterson and Squiers 1995), the species appears to replace itself in Canaan Valley. The virtual absence of red spruce regeneration in these stands may be an artifact of remoteness of seed source in the aftermath of logging and fires. However, there were other tree species such as yellow birch (*Betula alleghaniensis* Britt.), red maple (*Acer rubrum* L.), and eastern hemlock (*Tsuga canadensis* L. (Carr.)) that survived post-logging fires and were relatively abundant in upland areas, as well as in non-aspen swamp forests on the valley floor. Although these species are tolerant of shade and moist soils, and thus, a potential successor to aspen, they were not present in our study stands.

Based on tree age distribution at stand center, we estimate that initial aspen overstory mortality may occur at as early as 20 yr in this region. This is consistent with the observations of Krasny and Johnson (1992) that self-thinning (and stand development) occur very rapidly in clonal stands, but it is considerably less than estimates that the onset of stand breakup and decline occur at 45-80 yr in other regions (Fralish 1972, Shields and Bockheim 1981, Perala 1990, Kurzel and others 2007). However, aspen in the study area is at the edge of its southernmost distribution; across the species' North American range, there is considerable variation of the timing of dieback (Frey and others 2003), which may be influenced by climate and mean annual temperature (Shields and Bockheim 1981).

Selection of large and small trees along the distance gradient assumes that larger trees are older. We expected a strong d.b.h.-age relationship for trembling aspen, given its shade intolerance (Perala 1990), yet the linear relationship between age and diameter was surprisingly weak (large trees, $R^2 = 0.24$, small trees, $R^2 = 0.37$). Also, Leak and Graber (1974) developed their technique to detect stand expansion to investigate boundary movements over much longer time, distance, and elevational gradients, in response to regional climate shifts and disturbance patterns. In this study, distance gradients were only 12-38 m in length, and the number of sample trees available in such a short distance was limited. Both factors may tend to reduce the resolution of the technique and its ability to detect changes in stand boundaries at the distance and time scales of the study. Finally, although it is not uncommon for multiple clones to form a single stand, we did not identify separate clones/stand in this study. In cases where study stands were comprised of more than one clone, this would tend to distort the modeled age-size relationship from "center" to edge for expanding stands.

CONCLUSIONS

In Canaan Valley, the majority of aspen occurs in single-species stands that initiated between 1950 and 1970. Less than one-third of the stands appear to be expanding, and some of these are expanding at a very modest rate. The species composition and age distributions suggest that most stands have a component of stems that are older, than the median age as well as a component that is younger than the median age, which indicates that in addition to expansion at the edge, stand replacement—but not species change—is occurring at the stand center. Most stands do not appear to be expanding, limited either by competitive pressure from adjacent plant communities, unsuitable habitat, or genetics. Resource managers who wish to retain aspen for biological diversity and wildlife objectives should monitor stands for age and vigor. In addition to natural regeneration, they also may consider partial or complete overstory removal of older clones as an alternative way to stimulate ramet emergence and stand replacement.

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DEFERRED ROTATION HARVESTS IN CENTRAL APPALACHIA: 20- AND 25-YEAR RESULTS

Melissa Thomas-Van Gundy and Thomas M. Schuler[1]

Abstract.—In deferment harvest, two distinct age classes are created and the residual trees remain after establishment of the second cohort. The 20- or 25-year preliminary results from four deferment areas are described. For each area, volume and growth in the residual trees and new cohort, and structure and composition of the new cohort are presented. We also address whether the deferment harvest accomplished regeneration goals of establishing species that range from shade intolerant to tolerant.

INTRODUCTION

In the early 1980s concerns regarding the efficacy of regeneration practices promoted as alternatives to clearcutting prompted the initiation of this study. The practice under study, a hybrid between even-aged and uneven-aged silvicultural systems, is often referred to as deferment harvesting. In this system, two distinct age classes are created and residual trees remain after the second cohort is established. Study areas were established on the Fernow Experimental Forest and Monongahela National Forest in West Virginia to evaluate this system. Early results addressed concerns regarding composition of regeneration and growth of residual trees, but long-term results are necessary to fully understand this relatively new silvicultural system for the eastern United States (Smith and others 1989, Miller and Schuler 1995, Smith and others 1994, Miller 1996, Miller and others 1997).

Reasons for using deferment harvesting range from improved aesthetics (Smith and others 1989), to maintaining species diversity in regeneration (Miller and Kochenderfer 1998), and reducing negative impacts to wildlife (Miller and others 1995). While the improvement in aesthetics was not strongly supported by visual quality surveys (Pings and Hollenhorst 1993), songbirds appeared to benefit from the vertical structure created (Miller and others 1995).

Earlier results from the study have been reported. Five-year results concluded that the number and composition of stems were no different from those expected after a clearcut (Smith and others 1989). In 1995, 10-year results of residual tree growth and regeneration were combined with songbird count data (Miller and others 1995). Most residual trees in the deferred harvest areas showed greater diameter at breast height (d.b.h.) growth than trees of the same species in control stands (Miller and others 1995).

Survival, grade reduction, and regeneration results from deferment harvests on the Monongahela and Fernow were summarized by Miller and others (1997). The authors concluded that 89 percent of residual trees survived and initial grade was maintained on 76 to 100 percent of these trees depending on species. Also, d.b.h. growth of the residual trees increased for most species 2 to 5 years post-harvest. Regeneration after harvest was a mix of desirable commercial species and was similar to regeneration through clearcutting.

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Twenty-year post-harvest regeneration inventories showed that residual trees influenced growth and composition of regeneration in their immediate vicinity (Miller and others 2004, Miller and others 2006). Basal area of the regeneration increased with increasing distance from the reserve trees; basal area of shade-intolerant species more than doubled along the gradient.

OBJECTIVES

It has been 20 to 25 years since the creation of the deferment harvesting study on the Fernow and Monongahela. Reported here are the preliminary 20- or 25-year results from four of the six original areas. For each study area, two main topics are presented: volume in the residual trees and new cohort, and structure and composition of the new cohort.

STUDY AREAS

Study areas are on the Fernow Experimental Forest and the Monongahela National Forest in north-central West Virginia on the Allegheny Plateau province. Stands were unmanaged second-growth of mixed hardwoods before harvest with northern red oak (*Quercus rubra* L.) site indices ranging from 70 to 80 (base age 50). Age of initial stands was between 75 and 80 years at harvest. On all areas, annual average precipitation is about 59 inches and is distributed throughout the year. Average soil depth exceeds 3 feet (Miller and others 2004).

Results are reported for the Fish Trough, Shavers Fork, Riffle Creek, and Red House study areas. For Fish Trough and Shavers Fork, results reported here are 25 years after harvest; for Riffle Creek and Red House, results are 20 years post-harvest.

The Fish Trough area includes two sub-compartments (5.8 acres and 7.3 acres) established in 1981 on the Fernow Experimental Forest. The sub-compartments have similar site indices (80 for northern red oak), but differ in aspect. The sub-compartments were combined for reporting following an earlier assessment of no meaningful differences between the two areas. Harvest took place in the fall/winter of 1980-1981. Yellow-poplar (*Lirodendron tulipifera* L.) was the main species chosen for residual trees.

The Shavers Fork study area is 10.2 acres on the Monongahela with a northern red oak site index of 80. Yellow-poplar made up the majority of the residual trees. The area was harvested from May to August 1981.

The Riffle Creek study area was established in 1979 on the Monongahela and is approximately 14.8 acres with a northern red oak site index of 70. The area was logged during the spring of 1981. Red and white (*Q. alba* L.) oaks were favored as leave trees.

Established in 1985, the Red House study area is 8.9 acres on the Monongahela with a northern red oak site index of 80. Logging was completed in March 1985. Yellow-poplar, northern red oak, and black cherry (*Prunus serotina* Ehrh.) were featured leave trees. The dense striped maple (*Acer pennsylvanicum* L.) understory on about half (4.5 acres) of the study area was treated with herbicide before logging.

METHODS

Data collection methods for these study sites were reported earlier (Smith and others 1989, Miller and Schuler 1995). All study sites included the same data collection methods for regeneration, growth plots, and deferment trees.

Permanent regeneration plots were established on a 1 by 1, 1 by 2, or 1.5 by 1.5 chain grid in all areas to serve as plot centers for both small (<1.0 inch d.b.h.) and large (1.0 to 4.9 inches d.b.h.) regeneration; numbers of plots per study area vary from 47 to 60. All large woody stems, 1.0 to 4.9 inches d.b.h. were measured on 0.01-acre plots. Trees larger than 4.9 inches d.b.h. were recorded in large regeneration plots if they occurred in the area before the reestablishment of overstory growth plots. Our regeneration results include only stems 1.0 inch d.b.h. and larger. These regeneration surveys are used to describe stand composition and structure both before and after harvest.

Four 0.5-acre overstory growth plots were established in each study area with permanent center points before harvest and then again 20 years after harvesting. All trees 1.0 inch d.b.h. and greater were measured to the nearest 0.1 inch. These growth plots were used to describe vegetation both before and after harvest. On all study sites, all trees 1.0 inch d.b.h. and larger (except for the deferment trees) were cut during logging and site preparation.

Volume estimations were calculated from either growth plots or deferment trees alone. Cubic-feet volume was calculated for trees 5.0 inches d.b.h. and greater to a 4.0-inch top. Board-foot volume (International ¼ inch rule) was calculated for trees 11.0 inches d.b.h. and greater to an 8.0-inch top. Local volume Tables were used for both estimates.

Prelogging data for each residual tree consisted of: species, d.b.h., crown class, butt log grade, total height, crown width, clear bole length, merchantable height, epicormics by 8-foot sections, and general remarks. We do not address crown, bole, or grade characteristics in this paper. All deferment trees were permanently identified.

In this preliminary analysis, we examined diameter growth by site using standard analysis of variance procedures. We also used the Tukey-Kramer adjustment, which controls the experiment-wise error rate, for means comparison when statistical differences were identified ($\alpha = 0.05$ for all tests). Further analysis is planned to test for differences in species, species•site and species•time interactions.

RESULTS

Volume Growth—Residuals and Ingrowth

There were 174 residual trees, about 13 per acre (Table 1) at the Fish Trough site following harvesting. At age 25, 161 deferment trees remained, about 12 per acre. Net change (based on growth plot data) from year 1 to year 25 is an increase in total cubic foot volume of 1,580 and an increase of 4,549 board feet per acre (Fig. 1). Annual volume growth was approximately 182 board feet per acre or 63 cubic feet per acre. Stand volume was 21,787 board feet per acre before harvest; at age 25, stand volume has recovered to about 45 percent of the initial volume. Cubic-foot volume has grown to approximately 64 percent of the initial stand volume.

In the Shavers Fork study area, a total of 134 deferment trees (about 13 per acre) were selected (Table 1). The board-foot volume per acre for the deferment trees averaged 3,833 per acre and cubic-foot volume averaged 558 per acre immediately after harvest (based on measurements of residual trees). Net change (from growth plot data) from year 1 to year 25 is an increase of 1,675 cubic feet per acre and 4,687 board feet per acre (Fig. 1). Stand volume was about 14,483 board feet per acre before harvest. Board-foot volume at age 25 is about 58 percent of the preharvest average per acre. Cubic-foot volume has grown to

Table 1.—Summarized stand data for pre-treatment and most recent surveys. Preharvest and post-harvest data come from the 0.5-acre growth plots; preharvest data for the deferment trees alone come from individual tree measurements of all deferment trees.

	Trees per acre			Volume/acre (5” d.b.h. +)		Basal area (ft²/acre)		
Year	5.0”-10.9”	11”+	Total	Cubic ft.	Board ft	5.0”-10.9”	11”+	Total
				Fish Trough				
Preharvest	53	78	131	3,603	21,787	18.0	119.0	137.0
Preharvest (deferment trees)	0	13	13	667	4,786	0.0	24.0	24.0
1981 - year 1	0	15	15	722	5,290	0.0	26.0	26.0
2007 - year 25	174	20	194	2,302	9,838	46.0	52.0	98.0
				Shavers Fork				
Preharvest	91	60	151	2,698	14,483	27.0	82.0	109.0
Preharvest (deferment trees)	0	13	13	558	3,833	0.0	20.0	20.0
1982 - year 1	0	11	11	506	3,696	0.0	18.0	18.0
2007 - year 25	172	13	184	2,182	8,383	49.0	44.0	93.0
				Riffle Creek				
Preharvest	98	72	170	3,357	15,245	34.0	100.0	134.0
Preharvest deferment trees	1	11	12	478	2,612	0.7	16.7	17.4
1980 - year 1	1	11	13	537	2,999	0.6	19.0	20.0
2004 - year 20	85	13	98	1,528	6,709	19.0	42.0	61.0
				Red House				
Preharvest	70	128	198	4,833	28,218	25.0	162.0	197.0
Preharvest deferment trees	0	19	20	830	5,802	0.0	30.0	30.5
1985 - year 1	1	19	19	734	5,104	0.0	27.0	27.0
2004 - year 20	165	19	183	1,925	9,257	36.0	46.5	83.0

approximately 81 percent of the initial stand volume. Annual growth is approximately 187 board feet per acre or 67 cubic feet per acre.

For the Riffle Creek study area, leave trees averaged about 13 trees per acre (Table 1). Board-foot volume of the deferment trees averaged 2,612 per acre; cubic-foot volume averaged 478 cubic feet per acre. After logging, 184 trees were left on the study site. From year 1 to year 20, net growth (based on growth plot data) was 991 cubic feet of volume per acre and 3,710 board feet of volume per acre (Fig. 1). Annual growth was 161 board feet per acre and 43 cubic feet per acre. Board-foot volume at age 23 was about 44 percent of the pre-harvest total while cubic-foot volume was about 46 percent of total.

In the Red House study area, 174 deferment trees were chosen (about 20 per acre) and six were lost in logging, leaving about 19 per acre (Table 1). Volume in deferment trees averaged 5,547 board feet per acre in 1985 immediately post-logging. Net change from year 1 to year 20 was the addition of 1,191 cubic feet per acre and 4,153 board feet per acre. Annual board-foot volume growth was approximately 208 per acre and cubic foot volume growth was about 60 per acre (Fig. 1). Board-foot volume at age 20 is about 33 percent of the preharvest volume while cubic-foot volume is about 40 percent of the preharvest amount.

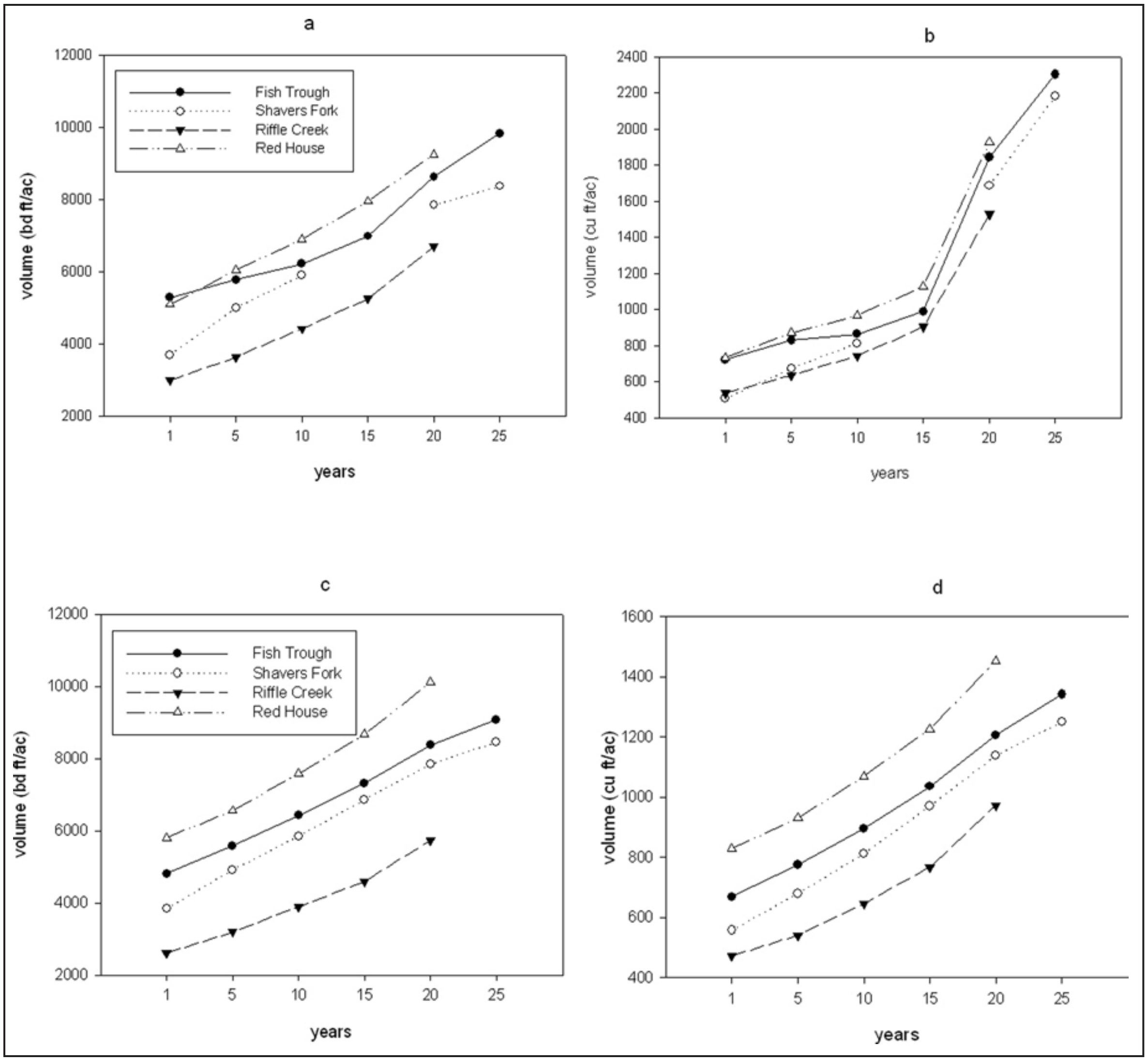

Figure 1.—Volume for each study area from post-logging to present; a) board foot volume from growth plots; b) cubic-foot volume from growth plots; c) board-foot volume from residual trees only; d) cubic-foot volume from residual trees only.

For the Fish Trough, Riffle Creek, and Red House areas cubic foot volume exhibits a distinct increase between 15 and 20 years post-harvest (Fig. 1). This increase marks the ingrowth of the new cohort from less than 5 inches d.b.h. to the pole-sized class. Similar ingrowth probably occurred around the same time on the Shavers Fork study area, but 15-year growth plot data are not available.

Diameter Growth of Residuals

Analysis of variance results indicated the diameter growth of residual trees differed by site for all measurement periods ($P < 0.05$ in each case). Shavers Fork consistently exhibited greater growth throughout the past two decades and was significantly different from the other three locations (Table 2), averaging more than 4 inches of d.b.h. growth per decade with all species combined. For the other locations, differences by site declined over time. Five years after treatment, each site exhibited a unique response in terms of diameter growth. However, after 20 years, only the Shavers Fork location was statistically discernable. Diameter growth ranged from 3.5 to 3.2 inches per decade after 20 years at Fish Trough, Riffle Creek, and Red House (Table 2). Diameter growth for central Appalachian species in unmanaged stands

Table 2.—Average annual diameter growth rates (inches/year) of deferment trees by site and measurement period. The Tukey-Kramer adjustment for means comparison was used to identify differences by site (α = 0.05) within 5-year measurement periods (mean differences indicated by lowercase letters).

Site	5 Years	10 years	15 years	20 years	25 years
Shavers Fork	0.51 a	0.43 a	0.41 a	0.42 a	0.37 a
Fish Trough	0.35 b	0.34 b	0.33 b	0.35 b	0.33 b
Riffle Creek	0.29 c	0.31 c	0.32 b	0.32 b	
Red House	0.24 d	0.30 c	0.30 c	0.32 b	
Combined	0.34	0.33	0.33	0.35	

Table 3.—Average annual diameter growth rates (inches/year) of deferment trees by location for selected species. Shavers Fork, Red House, and Riffle Creek were combined due to similarities in growth rates.

Species	5 Years	10 years	15 years	20 years	25 years
			Fish Trough, Red House, and Riffle Creek		
White oak	0.26	0.28	0.28	0.28	--
Northern red oak	0.32	0.37	0.39	0.41	0.47
Yellow-poplar	0.31	0.32	0.31	0.33	0.33
Black cherry	0.21	0.21	0.21	0.22	0.24
Sugar maple	0.32	0.31	0.31	0.32	0.26
			Shavers Fork		
White oak	0.47	0.44	0.44	0.43	0.38
Northern red oak	0.48	0.48	0.48	0.50	0.45
Yellow-poplar	0.53	0.41	0.39	0.40	0.35
Black cherry	0.46	0.41	0.40	0.39	0.35

is expected to be about 2 inches per decade for northern red oak, yellow-poplar, and black cherry, and somewhat less for white oak (Miller and others 1995).

Diameter growth differences by site could not be solely attributed to differences in the species composition of the residual trees. At Fish Trough, Shavers Fork, and Red House, the majority of residual trees were yellow-poplar, at 63, 57, and 64 percent, respectively. At these three sites, northern red oak was the second most abundant species of residual tree, at 12, 23, and 28 percent, respectively. At the Riffle Creek study area, northern red oak and white oak combined represented 75 percent of the residual trees, with yellow-poplar making up just 10 percent of the total.

Given the significant differences in diameter growth by site, we grouped Fish Trough, Red House, and Riffle Creek for a species assessment of growth rates, while Shavers Fork was kept separate (Table 3). We selected white and northern red oak, yellow-poplar, black cherry, and sugar maple for further analysis and reporting because of their commercial value and overall importance in the region, although sugar maple was not present as a deferment tree at Shavers Fork.

Growth rates were greatest for northern red oak for most measurement cycles. The Fish Trough, Red House, and Riffle Creek combined results show an increasing growth rate for northern red oak at each

5-year period that exceeded 4.5 inches per decade at the last measurement period. Shavers Fork northern red oak has maintained d.b.h. growth rates greater than 4 inches per decade for the past 25 years, which equates to adding about 10 inches of stem diameter in the last 25 years.

In contrast, yellow-poplar at Shavers Fork has slowed in diameter growth at each measurement cycle after an initially vigorous response (0.53 inches per year during the first 5 years). At the other three locations, yellow-poplar has maintained a steady growth rate of just over 3 inches per decade. Black cherry diameter growth responded favorably at the Shavers Fork location 5 years after treatment (0.46 inches per year), but growth has slowed at each subsequent measurement cycle. For the combined locations, black cherry growth rate was near the expected norm for unmanaged stands of about 2 inches per decade. Our results indicate black cherry is not always capable of responding vigorously to additional growing space associated with deferment harvesting. Shagbark hickory (*Carya ovata*, (P. Mill) K. Koch), chestnut oak (*Q. prinus* L.), and white ash (*Fraxinus americana* L.) also had 20-year post-treatment average annual d.b.h. growth rates of less than 0.25 inches per year.

Stand Structure and species Composition

Currently much of the regeneration established from the two-age harvest is represented by 6- to 10-inch d.b.h. stems. The growth plot data were summarized by area at year 20 or 25 to show stems per acre and crown position for commercial species by diameter class (Table 4).

In the Fish Trough and Shavers Fork areas, pole-sized regeneration is mainly dominant/co-dominant yellow-poplar. In the Riffle Creek area, yellow-poplar and northern red oak share dominance of the pole-sized regeneration. Riffle Creek has the lowest site index (70) of the four areas, while still relatively high; oaks appear to have an advantage on this site. Yellow-poplar was also dominant in the Red House area; however, unlike the other areas, black cherry stems were also competitive. Pole-sized pin cherry is still present in all study sites although they are a minor component.

Sugar maple, oaks, and black cherry were chosen to track from pre-harvest through the 20- or 25-year development of the second cohort (regeneration from 0.01-acre plots and pole-size stems from 0.5-acre growth plots) (Table 5). Sugar maple made up much of the large regeneration at the time of harvest, and is the main shade-tolerant species found in the large regeneration layer in most areas. White and chestnut oak were tracked in the Riffle Creek area along with northern red oak; on other areas, northern red oak was the only oak present as large regeneration.

On the Fish Trough site, northern red oak and black cherry large regeneration did not appear in the plots until 1991, 10 years post-harvest. Both species have persisted to the present as small saplings, and a minor percentage have moved into the pole-sized class at 20 years post-harvest. There has been a decline in stem density in the 1 to 4.9 inch d.b.h. class as the stand reached the stem exclusion stage between 15 and 20 years of age.

At the Shavers Fork site, there were two stems per acre (large regeneration) of northern red oak before harvest, increasing to 44 per acre 10 years after harvest, or about 4.5 percent of the total regeneration of commercial species (Table 5 does not include total). At 20 years post-harvest, northern red oak stems show movement into the pole-size class, but total only three per acre. Also at 20 years post-harvest, yellow-poplar, black cherry, and sugar maple regeneration moved into the pole-size class. Total commercial regeneration has declined since 15 years post-harvest as competition increased and stems moved into larger d.b.h. classes.

Table 4.–20- or 25-year stand structure—commercial species. D/C = dominant/codominant crown class, I/O = intermediate/overtopped crown class. Data are from the 0.5-acre growth plots.

	Stems per acre						
	6-10”		12-16”		18-24”		
Species	D/C	I/O	D/C	I/O	D/C	I/O	Total
Fish Trough							
Birch	19	2	0	0	0	0	21
Northern red oak	1	0	0	0	0	0	1
Yellow-poplar	69	25	6	0	9	0	109
Black cherry	4	1	0	0	1	0	6
Sugar maple	3	4	0	0	0	0	7
Red maple	0	1	0	0	0	0	1
Basswood	29	13	0	0	5	0	47
White ash	1	0	0	0	1	0	2
other	8	4	0	0	2	0	14
Total	134	50	6	0	18	0	208
Shavers Fork							
Birch	15	5	0	0	0	0	20
Northern red oak	2	1	0	0	4	0	7
Yellow-poplar	85	33	2	0	8	1	128
Black cherry	2	0	1	0	0	0	3
Sugar maple	2	1	0	0	0	0	3
Red maple	7	1	0	0	0	1	9
Basswood	2	3	0	0	0	3	8
other	13	10	0	0	0	1	24
Total	129	54	3	0	12	6	204
Riffle Creek							
Birch	6	0	0	0	0	0	6
White oak	1	0	0	0	7	0	8
Chestnut oak	8	1	0	0	0	0	9
Northern red oak	16	0	0	0	9	0	25
Yellow-poplar	18	3	1	0	1	0	23
Black cherry	6	1	0	0	0	0	6
Sugar maple	2	1	1	0	1	0	5
Red maple	14	6	0	0	2	0	22
other	4	1	1	0	0	0	6
Total	75	13	3	0	19	0	110
Red House							
Birch	10	0	0	0	0	0	10
Northern red oak	1	0	0	0	2	0	3
Yellow-poplar	86	6	0	0	13	0	105
Black cherry	46	2	1	0	6	0	55
Red maple	1	1	0	0	0	0	2
Basswood	1	0	0	0	0	0	1
White ash	0	0	1	0	0	0	1
Total	145	9	2	0	21	0	177

Table 5.—Stems per acre of selected species from preharvest to latest measurement. Data for stems less than 6 inches d.b.h. are from 0.01-acre regeneration plots and the 6-10 inches d.b.h. stems from 0.5-acre growth plots. Table displays data for selected species, not total found in study areas.

		oaks	black cherry	yellow-poplar	beech	sugar maple	oaks	black cherry	yellow-poplar	beech	sugar maple
				Fish Trough					Shavers Fork		
Preharvest	<6”	0	0	0	75	142	2	0	6	232	52
	6”	0	0	0	4	14	1	1	5	11	9
	8”	0	1	0	1	6	0	1	10	3	5
	10”	0	0	1	1	3	0	0	10	2	1
5 yrs	<6”	0	0	32	10	47	14	2	352	4	16
	6”	0	0	0	0	0	0	0	0	0	0
	8”	0	0	0	0	0	0	0	0	0	0
	10”	0	0	0	0	0	0	0	0	0	0
10 yrs	<6”	22	27	252	60	278	44	8	434	94	54
	6”	0	0	0	0	0	0	0	0	0	0
	8”	0	0	0	0	0	0	0	0	0	0
	10”	0	0	0	0	0	0	0	0	0	0
20 yrs	<6”	17	20	102	70	297	32	6	218	170	74
	6”	0	3	53	0	3	2	1	66	0	1
	8”	0	1	27	0	0	1	1	30	0	0
	10”	0	0	7	0	0	0	1	4	0	0
25 yrs	<6”	10	12	37	72	287	20	2	144	190	90
	6”	1	3	45	0	6	2	1	50	0	2
	8”	0	2	31	0	1	1	0	48	0	0
	10”	0	0	16	0	0	0	1	20	0	0
Preharvest				Riffle Creek					Red House		
	<6”	6	0	0	175	62	2	0	0	93	54
	6”	6	0	0	3	8	2	1	1	4	9
	8”	10	0	1	1	3	2	4	3	0	2
	10”	20	1	1	0	3	1	8	11	0	1
5 yrs	<6”	89	19	43	15	11	2	153	200	0	0
	6”	0	0	0	0	0	0	0	0	0	0
	8”	0	0	0	0	0	0	0	0	0	0
	10”	0	0	0	0	0	0	0	0	0	0
10 yrs	<6”	243	55	87	179	89	34	283	689	11	17
	6”	0	0	0	0	0	0	0	0	0	0
	8”	0	0	0	0	0	0	0	0	0	0
	10”	0	0	0	0	0	0	0	0	0	0
20 yrs	<6”	168	17	38	387	160	19	123	255	17	15
	6”	21	4	8	0	3	1	40	61	0	0
	8”	4	2	8	0	0	0	7	28	0	0
	10”	0	0	4	0	0	0	1	2	0	0

In the Riffle Creek area, there were six oak stems per acre in the large regeneration layer before harvest. At age 10 there were more oak stems than beech, sugar maple, or yellow-poplar when considered separately. At age 15, oaks contributed 283 stems per acre or about 20 percent of the total commercial species regeneration. Between years 15 and 20, the numbers of oaks declined to 168 per acre (13 percent). Beech stems have increased in number since harvest and now total 387 stems per acre (31 percent). As in the other areas, growth of stems into the pole-sized class is detected 20 years post-harvest. Unlike the other areas, oaks are competitive with yellow-poplar.

At the Red House site, yellow-poplar has dominated the regeneration since 10 years after harvest. There have been very few oak stems in this stand throughout the study period. A dense layer of striped maple limited advanced regeneration of commercial species preharvest. Movement of stems into the pole-sized class is noted at 20 years post-harvest.

DISCUSSION

Volumes in the study areas continue to increase as the new cohort develops and residual trees continue to increase in volume. Increased cubic-foot volume indicates that stand structure includes many smaller, pole-sized stems per acre than were in the initial stand. As shown in the growth of board-foot volume, vigorous growth of residual trees has, in some areas, recovered to 50 percent or more of the preharvest volume.

Regeneration in the new stand has reached pole size and is diverse. Yellow-poplar dominated the regeneration and the pole-sized stem classes in all but one area. This outcome is consistent with even-aged regeneration methods on similar high site indices in the Appalachians (Smith and others 1976, Loftis 1983, Beck and Hooper 1986, Loftis 1989, Brashears and others 2004). Black cherry has regenerated in the deferment harvests and could benefit from early release.

Shade-tolerant beech and sugar maple dominated the advanced regeneration in the areas before harvest. Current dominance by yellow-poplar reflects the open conditions created by the deferment harvest and possibly the seed source provided by the abundant yellow-poplar leave trees on most sties. Regeneration in the areas came from many sources: sprouts (basswood, oak); stored seed (black birch); advanced regeneration (sugar maple, beech); and new seed from surrounding forest and residual trees.

In previous assessments, deferment harvests resulted in an abundance of black birch hindering regeneration of other more desirable commercial species (Miller and Schuler 1995). Twenty-plus years after harvesting, we find black birch remains a significant component of the new cohort (Table 4). However, in the pole-sized stratum, birch is less abundant than other commercial species. In the Shavers Fork area, birch regeneration has declined in relation to other commercial species, but it has remained about the same at Fish Trough and increased at Riffle Creek. Birch makes up about 30 percent of the large reproduction in the Red House area. Birch is also present as pole-sized stems in all study areas, mainly in the dominant/codominant class.

On most of the study areas, pin cherry is a component of the pole-sized regeneration and often has the largest d.b.h. in the stand. Pin cherry is relatively short-lived, but can interfere with regeneration of more desirable species.

Miller and others (2004, 2006) discuss impacts the residual trees had on regeneration in these areas. Shade from the older cohort has limited development and species diversity under the crowns of the residual trees. Even with the documented impacts to regeneration from the residual trees, deferment harvesting as conducted may still meet many landowner objectives. Slower growth under the crown of and immediately adjacent to each residual tree may be acceptable given continued growth of high valued residuals, continued mast production, and continued presence of mature trees of species with regeneration difficulties under any silvicultural system. As documented here, species composition of the new cohort is diverse, with a large component of shade-intolerant species such as yellow-poplar. The high numbers of young (i.e., small d.b.h.) stems per acre in the areas at 20 or 25 years post-harvest indicate that there are still options in the stands to control species composition and growth through tending of the new cohort.

The low amount of oak regeneration and its gradual relegation to overtopped status, the influence of the residual overstory, and the abundance of low-quality competitors such as birch and pin cherry all point to the need for early precommercial thinning or crop tree release (Miller 2000, Schuler 2006). This analysis, as well as previous work, shows the need to capture the diversity in regeneration before desirable species and stems are irrevocably subordinated or lost altogether. Based on the 20- and 25-year results and previous analysis of these areas, this precommercial step should take place before age 20.

Given the absence of advanced oak regeneration before harvest, it is not surprising that young oaks are struggling to maintain a competitive position. Moreover, these areas were not dominated by northern red oak in the overstory before harvest and most regeneration methods would have led to a decline in oak abundance. Retention of some oak in the overstory can also be seen as "insurance" for the future as oaks continue to be a source for regeneration, provide hard mast for wildlife, and add diversity to the stand.

Expected growth rates and life expectancies are two criteria for selecting deferment trees. For example, black cherry did not always respond to release in this study and has a relatively short life expectancy. As such, black cherry would not be a good species to retain in a deferment harvest. In contrast, northern red oak does seem to maintain elevated growth rates after deferment harvesting for at least 25 years and has a life expectancy that can span a second rotation in a deferment harvest. Management objectives of deferment harvesting will more likely be achieved if species characteristics regarding growth, quality, and persistence are fully considered.

Deferment harvesting has become one of the most commonly applied new silvicultural techniques on both public and private lands in the central Appalachians in the last two decades. Growth of residual trees, abundance of regeneration, and structural characteristics that enhance wildlife habitat for both game and nongame species have all contributed to the interest and use of deferment harvesting. Forest managers using deferment harvesting on productive sites should consider crop tree release of the new cohort 15 to 20 years following the initial harvest. Partial reduction of declining or an over-abundant overstory during a crop tree release may be feasible, or even enhance, such an operation. Future work in this area should address these issues and also more fully investigate deferment harvesting on lower quality sites. Oak regeneration on some medium or lower quality sites with this technique appears promising.

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DIFFERENT HISTORIES BUT SIMILAR GENETIC DIVERSITY AND STRUCTURE FOR BLACK WALNUT IN INDIANA AND MISSOURI

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Abstract.—Missouri and Indiana have markedly different histories of glaciation and recolonization by forest trees. These states also differ in land use patterns and degree of anthropogenic landscape change such as forest fragmentation. To determine the overall effects of these and other demographic differences on the levels of genetic diversity and structure in black walnut (*Juglans nigra* L.) more than 550 total black walnut trees from nine populations in Indiana and 10 in Missouri were sampled and analyzed using 12 nuclear microsatellite loci. Although genetic diversity parameters such as allelic richness and expected heterozygosity were high overall, they varied little among populations and their mean values for the two states were not significantly different. Pairwise genetic distance values between all population pairs ranged from 0.012-0.159, but no significant pattern of isolation by distance was detected. The estimate of the degree of genetic differentiation between states (F_{PT} = 0.0009) was very small and not significant, indicating that differences between states explained an inconsequential portion of the total variance. The observed low levels of local and regional genetic structure indicate that high levels of pollen flow have buffered black walnut from the genetic consequences of founder effects and genetic drift in both geologic and recent time scales.

INTRODUCTION

Black walnut is currently one of the most economically important deciduous species in the Midwest (Hoover and Preston 2004, Jones 2004). Despite its economic importance, little is known about how differing natural histories and forest management regimes affect the genetic diversity and structure of this species.

The results of recent investigations of the genetic structure and the factors that determine patterns of genetic variability for black walnut indicated very little evidence of genetic variance partitioning at large spatial scales (Robichaud and others 2006, Victory and others 2006). The consideration of regional scale partitioning of genetic variance in black walnut might provide a clearer understanding of the impacts of glaciation, habitat quality, habitat loss, fragmentation, and demographic changes on the population genetics of this species. We analyzed a subset of populations from the broad scale analysis to investigate levels of genetic diversity and structure in regional black walnut populations from Indiana and Missouri. These two states were chosen for comparison because, despite their relative proximity: (1) their glacial histories are dissimilar; and (2) the patterns of land-use change and human disturbance over the past century differ considerably between these two states.

Indiana and Missouri have different histories of glaciation and recolonization by forest trees. The northern half of Indiana was glaciated during the last glacial episode, but Missouri was entirely unglaciated. During

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presettlement, the vegetation of the northwestern half of Missouri was mixed prairie and forest, whereas Indiana was covered almost entirely by deciduous forest (Dorale and others 1998). If palyonological records accurately reflect population levels, black walnut population levels have been marked by strong and dynamic fluctuations. Nevertheless, Indiana has almost always been near the center of black walnut's range, and except for the modern period, black walnut has been considerably more abundant in Indiana than Missouri for nearly all of the past 13,000 years (Williams and others 2004). Missouri's climate has been considerably drier than the climate of Indiana since the last glaciation (Thornwaite 1941, Dorale and others 1998), and since Missouri is near the periphery of black walnut's range, black walnut populations in Missouri may have experienced strong pressure for adaptational divergence (Garcia-Ramos and Kirkpatrick 1997).

Indiana and Missouri differ now both in terms of the total amount of forest land and in the proportion of land under agricultural production. According to the U.S. Geological Survey (2003), Indiana has approximately 73 percent of its total area in row crops, small grains, and hay production; by comparison, these crops occupy 54 percent of the land area of Missouri. In 1900, less than 7 percent of the original forestland remained in Indiana, and by 2002 that percentage had increased to only 22 percent, for a total forested area in Indiana of about 2 M hectares (Tormoehlen and others 2000). Although large areas of forest in Missouri also have been cleared, Missouri, unlike Indiana, has large tracts of continuous forest totaling 5.7 M hectares, almost 32 percent of its land area.

The silvics of black walnut differ markedly between the states as well; black walnut is relatively rare in Indiana compared to Missouri. The net volume of live black walnut on Indiana forest land, approximately 7,000 m^3, is less than the volume of nearly all other hardwood species (Moser and others 2004a). About one percent of the 7.3 billion trees in Missouri are black walnut (Vasievich and Kingsley 1995). The net volume for black walnut on Missouri's forest lands is approximately 13,500 m^3, surpassing all other species in the state except red and white oak species and other miscellaneous eastern soft hardwoods (Moser and others 2004b).

OBJECTIVES

Given that Missouri has more forested land, a higher density of black walnut in suitable habitat, more contiguous forests, and a different legacy of post-glacial recolonization than Indiana, we expected the genetic diversity and structure of black walnut to differ markedly between the two states. Thus, the goal of this study was to examine genetic differentiation within and among populations of black walnut in Indiana and Missouri, in order to understand the role of ecological and anthropogenic change in forming patterns of regional genetic structure.

STUDY AREAS

We sampled black walnut trees (n=552) from nine and ten natural populations in Indiana and Missouri, respectively, in 2001-2003 (Table 1). Sampled populations were located at least 1.6 km from any known black walnut plantation, and occurred in diverse ownerships (Table 1). The average distance between a population and its nearest sampled neighbor was 73.18 (± 40.2) km. Sampled trees within a population were spaced about 100 m apart or more. Leaf tissue (4 to 6 leaflets per tree) was collected from each sampled tree, placed into a resealable plastic bag, and mailed to Purdue University, where it was stored at -80 °C or freeze-dried until the DNA could be extracted.

Table 1.—Sampling locations, sample sizes, population sizes, and population descriptions for the sampled Indiana and Missouri black walnut populations

Population	County	Sample size	Description	Stand size (hectares)
Indiana				
IN-A	Sullivan	19	Private	180
IN-C	Morgan	30	Private	20
IN-D	Parke	30	Shades State Park	20+
IN-E	Jennings	30	State Forest	140
IN-F	Posey	29	Private	81+
IN-H	Harrison	29	Blue Spring Wildlife area	16
IN-K	Grant	29	Public	49[a]
IN-L	Carroll	30	Private	12[b]
IN-Y	Pulaski	30	Private	140
Missouri				
MO-A	Boone	30	Private	8
MO-C	Adair	30	Private	14
MO-D	Jefferson	30	Private	160
MO-E	Texas	30	Private	41
MO-F	Howard	30	Private	8
MO-G	Johnson/Pettis/Henry	29	Private	16[c]
MO-H	Boone	30	Private	16
MO-I	Clinton	30	Private	13
MO-J	Callaway	30	Private	12
MO-K	Cass	28	Private	10

[a]Three tracts totaling 49 ha
[b]Two fragments totaling 12 ha
[c]Size for population where majority of leaves were sampled

MATERIALS AND METHODS

DNA extraction, quantification, and genotyping were performed according to Victory and others (2006), using the same set of 12 microsatellite loci reported therein. For quality control, a suite of DNA samples with known genotypes were amplified with each Polymerase Chain Reaction (PCR) as a positive control, and one set was run with each of the three populations per gel as allele size standards. A negative control was included in each amplification set. As a further control, 30 individuals were selected at random and genotyped independently. Allele calls for this positive control group matched the previously determined alleles more than 95 percent of the time (data not shown).

Data analysis was as described in Victory and others (2006) except hierarchical F-statistics for a three-level hierarchy (state, population, individual) were calculated with GDA (Lewis and Zaykin 2001). Estimates were obtained for F_{IS} (=f), F_{IT} (=F), F_{SP} (=θ_S) and F_{PT} (=θ_P), where the subscript *I* stands for individual, *S* for subpopulation (local population or county within each state), *P* for population (state), and *T* for total. Confidence intervals (α = 0.05) around the hierarchical *F*-statistics were obtained by bootstrapping 20,000 times over the 12 loci. Analysis of a two-level hierarchy also was performed in GDA so that F_{ST} also could be estimated. An alternate test for differences in genetic parameters (e.g., rarefacted allelic richness, observed heterozygosity, and expected heterozygosity) among the 19 sampled populations – in which

Table 2.—Genetic diversity measures[a] for each microsatellite locus across the entire sample of 552 black walnut trees in 19 populations

Locus	n	Allele size range (bp)	Number of alleles	H_O	H_T	F_{IS}[b]
AAG 01	550	148 - 172	9	0.656	0.697	0.045
WGA 06	550	134 - 170	18	0.606	0.609	-0.002
WGA 24	530	221 – 253	16	0.860	0.884	0.010
WGA 27	539	200 - 248	24	0.857	0.886	0.013
WGA 32	546	163 - 231	33	0.908	0.935	0.011
WGA 69	542	162 - 186	11	0.576	0.595	0.021
WGA 72	542	134 - 160	13	0.620	0.594	-0.055
WGA 76	547	224 - 252	13	0.733	0.742	-0.005
WGA 82	540	154 - 238	41	0.919	0.966	0.031*
WGA 89	526	181 - 235	28	0.922	0.922	-0.019
WGA 90	550	138 - 190	25	0.904	0.909	-0.011
WGA 97	543	148 - 194	22	0.864	0.900	0.031
Mean	542	---	21.08	0.785	0.803	0.007

[a]n, sample size for locus; HO, observed heterozygosity; HT, total expected heterozygosity; FIS, within population inbreeding coefficient (index of panmixia).
[b]Asterisks indicate FIS estimates significantly greater than zero after sequential Bonferroni correction (alpha = 0.05).

multilocus genotypes were permuted among the populations 10,000 times, contingency tables constructed, and the log-likelihood statistic *G* used as a test statistic – was carried out with the aid of FSTAT (Goudet 1995). A matrix of pairwise genetic distances (*D*; Nei 1978) among all population pairs was generated using GDA. Because spatial coordinates were not taken for all sampled trees or populations, pairwise geographic distance values were calculated based upon the distance between the county seats of the counties in which the populations were sampled. The only exception to this method of calculating geographic distance was for population MO-A, for which geospatially referenced global positioning system (GPS) coordinates specific to that population were used; this step was necessary since population MO-H was sampled in the same county and thus shared the same county seat. A Mantel test of association between the pairwise genetic and geographic distances was performed using the ISOLDE program of GENEPOP (version 3.4, de Genetique et Environment, Montpellier, France) (Raymond and Rousset 1995, Rousset 1997); 10,000 permutations were employed to obtain the *p*-value.

RESULTS

Complete genotypes at all 12 microsatellite loci were obtained for 98 percent of all sampled individuals. Based upon the overall sample of 552 individuals, the average genetic diversity across loci was high (Table 2), as measured by observed heterozygosity (H_O = 0.785), the average number of alleles per locus (A_N = 21.1), and the total number of alleles per locus, which ranged from nine (AAG 01) to 41 (WGA 82). Hardy-Weinberg genotypic proportions were rejected for only one of the 12 loci (WGA 82), on the basis of the permutation test (using F_{IS} as a test statistic) and after sequential Bonferroni correction (Table 2). The very large number of alleles at this locus (41 alleles) was likely a contributing factor. Low-frequency null alleles also may have been present at WGA 82.

Table 3.—Comparison of genetic diversity measuresa between Indiana and Missouri

Population	n	A_N	$A_{R(18)}$	$A_{R(23)}$	H_O	H_S	F_{IS}	F_{ST}
Indiana								
IN-A	18.8	10.0	9.87	------	0.787	0.782	-0.006	
IN-C	28.8	11.8	10.19	11.03	0.769	0.794	0.033	
IN-D	29.6	11.8	9.93	10.86	0.756	0.758	0.002	
IN-E	28.5	11.8	10.45	11.27	0.792	0.810	0.023	
IN-F	28.1	11.9	10.39	11.25	0.791	0.805	0.017	
IN-H	28.3	12.5	10.78	11.76	0.783	0.805	0.027	
IN-K	29.0	12.8	11.06	11.98	0.792	0.802	0.015	
IN-L	29.7	11.7	10.19	10.97	0.801	0.797	-0.006	
IN-Y	29.9	12.1	10.23	11.13	0.769	0.794	0.032	
IN mean	27.8	11.8	10.34	11.28	0.782	0.794	0.015	0.0128
Missouri								
MO-A	29.8	11.7	10.15	10.92	0.791	0.795	0.005	
MO-C	29.8	12.1	10.17	11.10	0.813	0.789	-0.031	
MO-D	29.3	12.1	10.29	11.21	0.794	0.799	0.006	
MO-E	29.1	11.3	10.03	10.72	0.785	0.797	0.015	
MO-F	29.8	12.8	10.58	11.63	0.782	0.803	0.027	
MO-G	28.8	12.3	10.48	11.40	0.805	0.798	-0.009	
MO-H	29.5	11.2	9.25	10.19	0.767	0.731	-0.050	
MO-I	28.7	11.7	10.07	10.92	0.763	0.777	0.018	
MO-J	29.3	12.7	10.83	11.81	0.782	0.791	0.011	
MO-K	27.4	12.1	10.36	11.36	0.805	0.800	-0.006	
MO mean	29.2	12.0	10.22	11.13	0.789	0.788	-0.001	0.0182
p-value[b]	----	----	0.259	0.480	0.163	0.256	0.032	0.198
Overall mean	28.5	11.9	10.28	11.20	0.786	0.791	0.007	0.0155

[a]n, avg. sample size per locus (based on 12 loci); A_N, avg. number of alleles per locus; $A_{R(18)}$, allelic richness standardized to a sample size of 18 trees per population; $A_{R(23)}$, allelic richness standardized to a sample size of 23 trees per population (IN-A omitted); H_O, within-population observed heterozygosity; H_S, within-population expected heterozygosity; F_{IS}, inbreeding coeffcient (or 'index of panmixia'); F_{ST}, fixation index for each state (measure of population differentiation).

[b]For the comparison of IN mean vs. MO mean, based upon 10,000 permutations of populations among states (one-tailed test).

All of the genetic diversity measures were markedly similar across populations, both within and between states (Table 3). The mean number of alleles per population ranged from 10.0 to 12.8 for Indiana and 11.2 to 12.8 for Missouri. Rarefaction to common sample sizes of 18 (with all populations) or 23 (excluding IN-A) reduced these ranges. Within-population observed heterozygosties ranged from 0.756 to 0.801 in Indiana and from 0.763 to 0.813 in Missouri. Permutation tests for differences in genetic diversity measures between Indiana and Missouri were not significant for all measures except mean F_{IS} (0.015 in Indiana vs. -0.001 in Missouri; $p = 0.032$). This result could be interpreted as indicating that in recent generations, matings between relatives (and/or selfing) have occurred at an elevated rate in Indiana populations relative to Missouri populations, possibly due to more severe fragmentation in Indiana. However, the effect is not very strong (F_{IS} in Indiana = 0.015); the global value of F_{IS} (across loci) was

Table 4.—Hierarchical F-statistics[a] across 12 loci for black walnut subpopulations grouped by state (Indiana versus Missouri) and associated confidence intervals (based on 20,000 bootstraps)

	F_{IS}	F_{IT}	F_{SP}	F_{PT}
Estimate	0.007	0.023	0.017	0.0009
Lower Bound[b]	-0.007	0.010	0.014	-0.0002
Upper Bound	0.019	0.035	0.019	0.0019

[a]Subscripts: I, individual; S, subpopulation (local population or county within a state); P, population (state); T, total.
[b]Lower and upper bounds for confidence intervals indicate statistical significance (alpha = 0.05) if zero is not included.

significantly different from zero ($p = 0.011$). However, both of these results were due to a single locus, WGA 82, so we caution against over-interpreting the somewhat elevated mean FIS in Indiana.

Twenty-three private alleles were observed (i.e., alleles occurring in only a single population sample; data not shown). In general, these private alleles were evenly distributed across the populations. All of the private alleles were present at low frequencies in the overall sample ($P < 0.005$) and all occurred at or very near the ends of the allele size range for each locus, indicating that they may have been recent mutations. Most of the private alleles were rare in the population where they were found, usually at a frequency of less than 0.05. Overall, the distribution of private alleles among the populations suggests that they are the products of sampling error rather than limited gene flow.

Hierarchical F-statistics (Table 4) provided little evidence of genetic structure between states: F_{PT} was estimated as 0.0009 and was not significantly different from zero (based upon bootstrapping loci). Hence, the additional hierarchical level to evaluate differences between states explained an inconsequential portion of the total variance. The estimate of the amount of differentiation among populations within states (F_{SP}) was small (0.017) but significant. The estimate of the amount of differentiation among populations regardless of their state of origin ($F_{ST} = 0.016$; obtained from a two-level analysis) was significant ($p < 0.05$). The estimate of F_{IS} was low (0.007) and not significantly different from zero (Table 4), reflecting the fact that most loci displayed Hardy-Weinberg genotypic proportions within populations (Table 2). An essentially identical result was obtained when the data were analyzed using Peakall and Smouse's R statistics (Peakall and Smouse 2006).

Pairwise genetic distance values varied from 0.012 to 0.159, indicating a broad range in the level of differentiation between population pairs. However, the Mantel test for isolation by distance indicated no significant association between geographical and genetic distance ($p = 0.29$).

DISCUSSION

Black walnut in Indiana and Missouri contains high levels of genetic diversity at nuclear microsatellite loci and is remarkably genetically homogenous. The overall level of genetic variance partitioned among all populations in the sample was quite small ($F_{ST} = 0.016$)—though statistically significant ($P < 0.01$). The data were devoid of any clear pattern of geographical structure. We found very little evidence of genetic variance partitioning among populations either within states or between states, confirming that the lack of genetic differentiation exhibited among black walnut populations at broad spatial scales (Victory and others 2006) also extends to smaller regional populations, despite local differences in glaciation history, fragmentation, and forest management practices. Also, we found no evidence for differences in mean population genetic diversity parameters between the two states (with the exception of mean F_{IS}, a result that was due solely to the somewhat aberrant locus WGA 82). Given the divergent natural histories of black walnut in Indiana and Missouri, the overall lack of contrast between the two states was surprising.

A number of factors might individually or collectively explain the observed lack of structure, including: (1) post-glacial recolonization of the current geographical distribution of black walnut from a single, large, homogenous glacial refugium; (2) the homogenization of black walnut gene frequencies (a) subsequent to post glacial recolonization and (b) subsequent to the anthropogenic bottlenecks of the last century; (3) high rates of size homoplasy (the potential to share alleles that are identical in size but not identical by descent) among microsatellite alleles in this species; and (4) large effective population size and high rates of gene flow in this species. Almost certainly each of these factors contributed in some way to the current population structure of black walnut in Indiana and Missouri.

High rates of pollen flow among neighboring refugial populations would have homogenized their gene frequencies and reduced overall genetic structure (effectively creating a single, large refugial population). The recolonization process for black walnut after the Last Glacial Maximum (LGM) may have been different for Indiana and Missouri, but whatever the differences may have been, they left no mark that we could detect using our data. Such a mark, if it once existed, may have been erased by extensive pollen flow subsequent to recolonization.

Differing regimes of deforestation and fragmentation that occurred in Missouri and Indiana after European settlement apparently have had little if any effect on the current neutral genetic diversity of black walnut in these states. Since deforestation was most extensive in portions of the species range that were highly suitable for agriculture (e.g., northern Indiana), numerous rare and localized alleles undoubtedly have been lost. Although it is likely that a high percentage of black walnut greater than 150 years of age has been harvested, it is probable that an insufficient number of generations have passed for the effects of forest fragmentation and anthropogenic selection to be discernable (Collevatti and others 2001).

In black walnut, as in other species, the presence of size homoplasy could homogenize the allelic diversity of populations (Estoup 2002). Our data exhibited two characteristics that may indicate the presence of size homoplasy. First, the allele distributions at each locus were relatively uniform across populations (not shown), indicating that most populations had retained or obtained through mutation a common set of allele sizes. Second, all of the private alleles detected occurred at the ends of the distribution of allele sizes, probably because novel mutations at each locus were detected only at the most extreme allele size classes. Homoplasy may have disrupted any traces of allele loss caused by founder effects present in either Indiana or Missouri black walnut populations (see Young and others 1993). Size homoplasy, however, does not fully explain the lack of allele frequency differentiation observed in this study, as studies in other tree species have uncovered pronounced genetic structure (Jones and others 2002, Heuertz and others 2004a).

The reproductive biology of walnut may best explain the current homogeneity within and between the black walnut populations in Indiana and Missouri. High levels of post-glacial gene flow can obscure, at the nuclear level, evidence of ancient population differentiation (Finkeldey and Matyas 2003, Heuertz and others 2004b). Black walnut seems to possess the necessary biological attributes to create and maintain large homogenous complexes of interacting populations and large effective population sizes even in the face of substantial vicariance.

The results reported here indicate that recent landscape changes in the Midwest, while significant, have not yet led to forest islands where the consequences of founder effects and genetic drift dominate the observed diversity of forest trees, at least not for black walnut. Now that there are unusually low population densities of black walnut in the center of its range (in Indiana), gene flow into populations at the periphery (e.g., Missouri) may be reduced, and peripheral populations may become less constrained in their adaptive evolution (Garcia-Ramos and Kirkpatrick 1997).

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VARIATION IN FLOOD TOLERANCE OF CONTAINER-GROWN SEEDLINGS OF SWAMP WHITE OAK, BUR OAK, AND WHITE OAK

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Abstract.—How much variation in flood tolerance exists among seedlings within oak species, given the flood frequency of sites from which acorns are collected, has been largely unexplored. Our studies examined initial growth and flood tolerance for seedlings of swamp white oak (*Quercus bicolor* Willd.), bur oak (*Q. macrocarpa* L.), and white oak (*Q. alba* L.) grown from acorns collected from both upland and bottomland sites. Two-flush seedlings grown in a soil-less potting mix were subjected to partial inundation for 0, 4, and 8 weeks with stagnant water in a shade house covered with 50 percent shade fabric. Only 40, 20, and 13 percent of the seedlings for swamp white, bur, and white oak, respectively, produced a new growth flush following partial inundation flooding. Seedlings of all three species produced hypertrophied lenticels in response to partial inundation. Swamp white oak seedlings that flushed averaged 17 cm of new height growth across all flood treatments in contrast to bur and white oak seedlings, where net height growth decreased with increasing flood duration. Bur and swamp white oak seedlings from bottomland seed sources showed greater basal diameter growth than seedlings from upland sources before and after flooding. The reverse was true for white oak seedlings. Highly significant differences in seedling growth and flood tolerance both for topographic position within species and among half-sib family within position indicate adequate variation exists within native populations of all three species to identify seed sources for improved planting stock for bottomland plantings.

INTRODUCTION

Flood tolerance is defined as the physiological adaptation of plant roots to anoxic conditions, toxic substances, and other associated changes in soil properties induced by flooding (Gardiner and others 1993, Kabrick and others 2007, Unger and others 2007). Flood tolerance ratings for the major hardwood species in the Central Hardwood Region have been reported by several research groups (Hook 1984, Kabrick and Dey 2001, Allen and others 2001). The assignment of oaks (*Quercus* spp.) to flood tolerance classes ranging from intolerant to tolerant is based largely on case-studies following natural flooding events and a few greenhouse studies (Hosner and Leaf 1962, Bell and Johnson 1974, Whitlow and Harris 1979, Hook 1984, Loucks 1987).

Flood facility and greenhouse studies have confirmed the assignment of oaks to classes ranging from intolerant, that is, withstanding only short-duration flooding, to tolerant, that is, the capacity to withstanding partial inundation for up to one growing season (Gardiner and others 1993, Kabrick and others 2007). When constructed on bottomland sites, field flood facilities can mimic natural flooding events with some control of the timing, duration, and depth of flooding and allow for testing of large numbers of seedlings (Lockhart and others 2006, Coggeshall and others 2007, Kabrick and others 2007, Van Sambeek and others 2007). Greenhouse-type studies that offer greater control of the flood

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environment are still needed to provide more detailed information on the physiological, morphological, and genetic responses of individual seedlings to flooding (Tang and Kozlowski 1982, Gardiner and others 1993, Ponton and others 2002, Kaelke and Dawson 2003).

Battaglia and others (2004) suggest that many oak species have the capacity to grow on both upland and bottomland sites. Within the Central Hardwood Region, bur (*Q. macrocarpa* L.) and swamp white (*Q. bicolor* Willd.) are two oak species that can be found in natural stands ranging from droughty upland to frequently flooded bottomlands (Kurz 2003). Several studies on other hardwoods indicate the need to carefully consider the seed source for production of seedlings for bottomland plantings. Keeley (1979) reported that seedlings of black gum (*Nyssa sylvatica* Marsh.) from bottomland seed sources had better survival and greater biomass than seedlings from upland sources. Later, Anella and Whitlow (1999) found that flooding red maple (*Acer rubrum* L.) for 28 days decreased net photosynthesis and growth of seedlings from upland seed sources more than from bottomland seed sources. Subsequently, Baurele and others (2003) showed that red maple has distinct ecotypes based on their response to flooding.

OBJECTIVES

The objectives of this study were to determine if collecting acorns from bottomland and upland stands affects seedling growth before, during, and following flooding and to determine the extent of seedling variation that exists among half-sib families of swamp white, bur, and white oak (*Q. alba* L.). Primarily, we wanted to determine if acorns collected from upland stands produce seedlings that are maladapted for planting on bottomland sites subject to flooding and if sufficient variation for flood tolerance exists within native populations to initiate breeding programs to produce improved oak planting stock for restoration of bottomland forests.

MATERIALS AND METHODS

From 15 September through 31 October 2005, acorns were collected from 10 swamp white oak, eight bur oak, and six white oak trees in central Missouri (Table 1). Each mother tree was assigned to either an upland or bottomland topographic position based on landscape position, soil series, drainage class, and flood frequency from information available at http://cares.missouri.edu website. Upland collection sites were typically on shoulder to summit slope positions that had not experienced any known flooding. Bottomland collection sites had experienced flooding either as short-duration flash-flooding or long-duration flooding such as in the Midwest floods of 1993 and 1995. Acorns from individual tree collections were stored in a walk-in cooler at 4 °C in 4-L plastic zipper bags punched with holes for air exchange.

On 28 November 2005, germinating acorns of each half-sib white oak family were placed on separate 40 x 40 x 13-cm deep polypropylene propagation flats with open lattice bottoms (Anderson Die and Manufacturing Co., Portland, OR). Trays were filled with a soil-less horticultural potting mix (10:4:4:1:1 by volume of pine bark, peat moss, vermiculite, perlite, and sand, respectively, amended with 0.5 L m^{-3} slow-release NH_4NO_3, urea, and micronutrients). Emerging radicals were placed into the potting medium and acorns covered. Flats were enclosed in polyethylene bags and set in the walk-in cooler at 4 °C until 16 February 2006.

On 13 February 2006, acorns of bur and swamp white oak were removed from cold storage, soaked in cold tap-water for 48 hours, and then float-tested. Twenty-five acorns of each half-sib family that did not float were measured for length and width to determine acorn volume (Rink and Coggeshall 1995). Remaining acorns were placed by families on separate propagation flats filled with the above potting mix.

Table 1.—Site characteristics, mother tree d.b.h., and mean acorn volume for the 24 half-sib families of the three oak species evaluated for initial seedling growth and flood tolerance

Species[1]	Topo-graphic position	Family name[2]	DBH (cm)	Acorn vol. (cm^3)	Slope position	Soil series[3]	Drain class[4]	Flooding frequency[5]
WHO	Upland	BN12W	79	----	Summit	Keswick SL	MWD	None
WHO	Upland	BN21W	61	----	Shoulder	Jamerson SL	WD	None
WHO	Upland	BN23W	122	----	Summit	Armstrong L	SPD	None
WHO	Upland	OS12W	46	----	Summit	Gravois L	MWD	None
WHO	Bottom	CO11W	102	----	Floodplain	Moniteau SL	VPD	Occasional*
WHO	Bottom	CO12W	114	----	Floodplain	Moniteau SL	VPD	Occasional*
BRO	Upland	AD11B	76	8.4	Shoulder	Gara L	MWD	None
BRO	Upland	BN11B	36	11.2	Shoulder	Weller SL	WD	None
BRO	Upland	BN12B	66	12.4	Shoulder	Weller SL	WD	None
BRO	Upland	SH11B	69	13.2	Foot slope	Viration GSL	WD	None
BRO	Bottom	BN21B	234	13.8	Floodplain	Darwin SCL	VPD	Occasional*
BRO	Bottom	BN31B	165	16.2	Floodplain	Haymond SL	MWD	Frequently
BRO	Bottom	CA11B	102	12.1	Floodplain	Belknap SL	SPD	Frequently
BRO	Bottom	HW11B	152	14.4	Floodplain	Hayne SL	SPD	Occasional*
SWO	Upland	AD12S	56	3.9	Shoulder	Gara L	MWD	None
SWO	Upland	AD14S	58	3.5	Shoulder	Gara L	MWD	None
SWO	Upland	BN22S	43	4.9	Summit	Weller SL	MWD	None
SWO	Upland	CA21S	76	3.5	Summit	Mexico SL	SPD	None
SWO	Upland	CA22S	81	4.4	Summit	Mexico SL	SPD	None
SWO	Bottom	BN12S	91	5.0	Floodplain	Perche L	VPD	Frequently
SWO	Bottom	BN13S	81	5.3	Floodplain	Perche L	VPD	Frequently
SWO	Bottom	CO11S	137	5.5	Floodplain	Moniteau SL	VPD	Occasional*
SWO	Bottom	PK11S	122	3.9	Terrace	Okaw SL	VPD	Rarely*
SWO	Bottom	PK21S	53	4.6	Floodplain	Twomile SL	VPD	Occasional*

[1]WHO=white oak, BRO = bur oak, SWO = swamp white oak.
[2]Family names indicate county, stand, tree number within stand, and species where AD = Adair, BN = Boone, CA = Callaway, CO = Cole, HW = Howard, OS = Osage, PK = Pike, and SH = Shannon County.
[3]Soil abbreviations: L = loam, S = silt, C= clay, and G = gravelly
[4]Drainage classes: VPD = very poorly drained, SPD = somewhat poorly drained, MWD = moderately well drained, and WD = well drained.
[5]An asterisk indicates the tree was partially inundated in 1993 and/or 1995.

On 16 February 2006, all propagation flats were placed on wire-mesh benches in a heated greenhouse maintained at 23 °C transmitting 50 to 60 percent of full sunlight without supplemental lighting. On 20 March 2006, one-flush air-root pruned seedlings were transplanted into individual 24-cm tall, 1.65-L slotted bottom treepots (Stuewe and Sons, Inc., Corvallis, OR) filled with the above potting mix and allowed to grow a second flush. On 10 May 2006, seedlings were moved to a large shade house covered with 50 percent shade cloth to acclimate to ambient summer temperatures and natural light.

Beginning on 29 May 2006, seedlings were flooded for 0, 4, or 8 weeks. Three individually tagged seedlings of each half-sib family had been placed in one of twelve 1,126-L galvanized stock tanks housed in the above shade house. Seedlings of each species were kept together, with the white oak seedlings located at either end of the tank to reduce shading by the taller bur and swamp white oak seedlings. The three seedlings for each family were randomly placed within a species block regardless of topographic acorn origin. Flooded seedlings were partially inundated to a depth of 5 cm above the potting mix.

Flood water was replenished twice a week using water under pressure pumped from an on-site catchment pond. During post-flood recovery, water was drained from the stock tank and seedlings watered as needed until harvested using the same source of water. No attempt was made to control water temperature; however, the study was done under black polyethylene shade cloth to reduce heating of the flood water. We used 50 percent shade cloth assuming a light compensation point of less than 50 percent of full sunlight for seedlings of all three oak species based on previous research with other oak species (Kozlowski 1949, Ponton and others 2002).

Data on survival, number of flushes, height above the soil line, basal diameter at 2.5 cm above the soil line, and occurrence of hypertrophied lenticels were determined at the initiation of flooding treatments (29 May 2006), termination of the 4-week flood (26 June 2006), termination of the 8-week flood (24 July 2006), and post-flood recovery (21 August 2006). At the end of the growing season (2 October 2006), seedlings were destructively sampled to determine number and area (LI-3000, Li-Cor Inc., Lincoln, NE) of leaves by flush, leaf and stem weight by flush, and root dry weight in addition to previous measurements. Five seedlings of each half-sib family were also destructively sampled on 29 May 2006 for pre-flood measurements.

Analysis of variance using PROC GLM (SAS Institute, Inc., Cary, NC) was used to determine if differences existed due to flooding, species, position within species, family within position, and their interactions. The experimental design was a randomized complete block for a split, split-plot design with four replications of three flood treatments as main plots, three species as sub-plots, and two to five half-sib families within the two topographic positions as sub-sub-plots. Family means were calculated from three seedlings for each combination of block and flood treatment before testing for normality using PROC UNIVARIATE. Duncan's new multiple range test was used for mean separations of main effects with statistical differences at alpha = 0.05 percent. Fisher's unprotected least significant difference was calculated from appropriate error mean squares and t-values to evaluate interaction with statistical differences for alpha = 0.01 percent. When family means for count or percentage data were not normally distributed, a Chi-square analysis was used to test for differences.

RESULTS

Seedling survival was high for all three species with no mortality in the non-flooded control. Approximately 1 percent (11 of 864) of the seedlings partially inundated for 4 weeks died. Less than 1 percent of bur and swamp white oak seedlings (5 of 648) and 11 percent of the white oak seedlings (24 of 216) died when flooded for 8 weeks. Survival of white oak from bottomland seed sources was greater than survival from upland seed sources, with the highest mortality in upland families OS12W and BN21W ($X^2 = 44.57$, $p < 0.001$).

Differences existed among species and position within species for stem length before flooding (Fig. 1). The two-flush swamp white and bur oak seedlings grown from the bottomland seed families produced longer flushes than seedlings from the upland families ($p < 0.001$). In contrast, the white oak seedlings from the four upland families produced longer second flushes than did seedlings from the two bottomland families. Differences ($p < 0.001$) existed among families within all positions within species except for the five families within the swamp white oak upland sources (Walsh 2007).

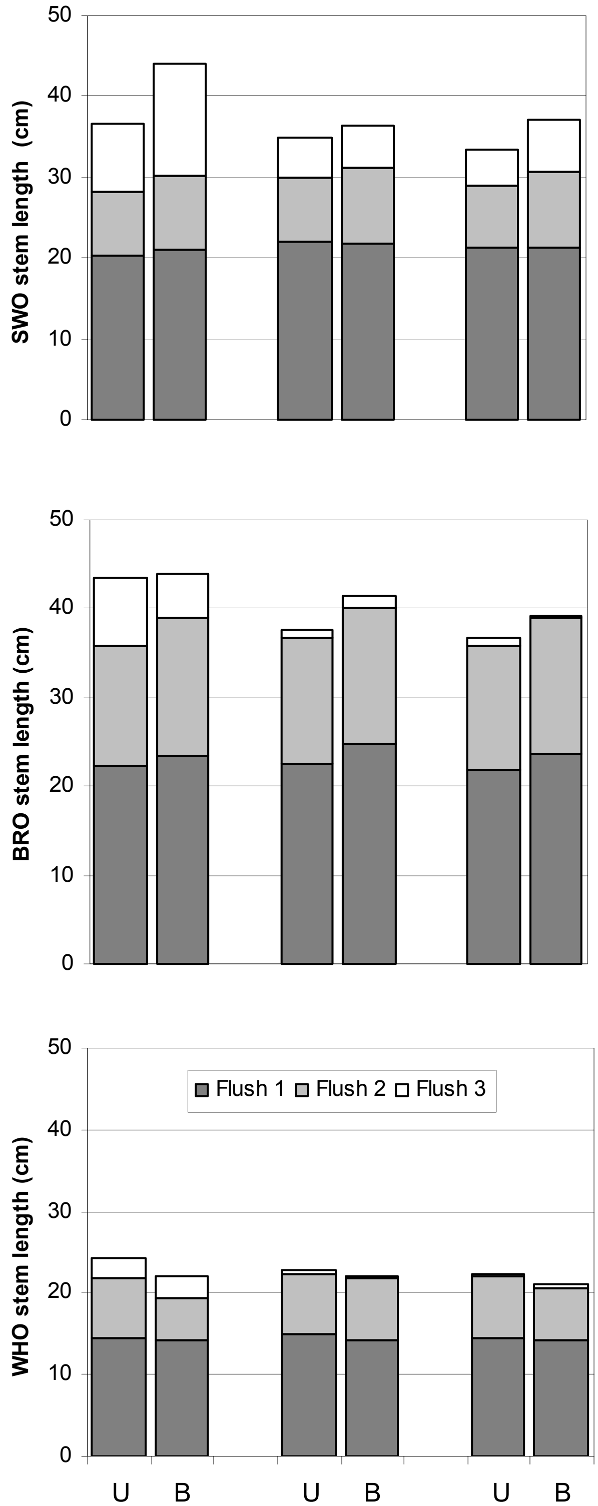

Figure 1.—Preflood stem length (flush 1 + 2) and post-flood new shoot growth (flush 3) for white oak (WHO), bur oak (BRO), and swamp white oak (SWO) seedlings produced from upland (U) and bottomland (B) natural stands subjected to mid-season flooding for 0, 4, and 8 weeks.

Following initiation of flooding and during post-flood recovery, new shoot growth, shown as stem length for the third flush in Figure 1, declined for all three oak species with increasing duration of flooding. Data for length of the third flush were calculated as the mean for all seedlings without deleting those that failed to initiate a third flush. Following initiation of the mid-season flooding treatment, only 13, 20, and 43 percent of the white, bur, and swamp white oak seedlings, respectively, flushed or increased in height (table 2). The percentage of seedlings with new shoot growth following initiation of flood treatments was

Table 2.—Percentage of seedlings producing new shoot growth following initiation of flood treatments that originated from upland and bottomland seed sources of white, bur, and swamp white oak

Oak species	Topographic position	Flood duration			Pos. mean
		0-wk	4-wk	8-wk	
White oak	Upland	21	13	12	15
	Bottomland	21	4	8	11
Bur oak	Upland	50	8	21	26
	Bottomland	25	10	8	14
Swamp white	Upland	55	32	28	38
	Bottomland	68	28	48	48
Weighted means		43	18	23	

greater within the control treatment than in both the 4-week and 8-week flood treatments (43, 18, and 23 percent, respectively). A higher percentage of swamp white oak seedlings from bottomland seed sources flushed versus upland seed sources (48 verses 38 percent, $X^2 = 47.41$, $p < 0.001$). In contrast, a higher percentage of bur oak seedlings from upland seed sources flushed compared to bottomland seed sources (17 versus 14 percent, $X^2 = 21.13$, $p < 0.001$). The lack of a third flush and no new height growth on most seedlings following initiation of flood treatments precluded analyses for differences among families within position within species.

Before initiation of the flood treatments, the two-flush seedlings from bottomland seed sources of both bur and swamp white oak had greater stem basal diameter ($p < 0.001$) than seedlings from upland seed sources (shown as 0 DAT [0 days after initiation of flood treatments] in Fig. 2). In contrast, seedlings of white oak from upland sources had greater stem diameter than seedlings from bottomland sources. Differences ($p < 0.001$) existed in basal stem diameter of two-flush seedlings among families within all positions within species except for the five families within the swamp white oak upland sources (Walsh 2007).

During the 28 days after the flooding treatments were initiated, the basal diameter growth for flooded seedlings of white oak from both upland and bottomland sources slowed by more than 50 percent compared to the non-flooded controls (28 DAT in Fig. 2). Post-flood diameter growth rates for white oak seedlings flooded for 4 weeks appeared to recover while growth rates of seedlings flooded for 8 weeks did not, especially for seedlings from the two bottomland seed sources.

Seedlings of both bur and swamp white oak had greater basal diameter growth while flooded ($p < 0.001$) than did the seedlings in the non-flooded control (28 DAT in figure 2). Although 75 percent of the surviving flooded white oak seedlings produced hypertrophied lenticels, these seedlings did not show greater diameter growth than the non-flooded control seedlings, which was in contrast to what was observed with bur and swamp white oak seedlings ($p = 0.006$). At the end of the growing season, basal diameter of bur and swamp white oak seedlings from the bottomland seed sources were larger than seedling basal diameters for upland seed sources ($p < 0.001$). The interaction for flood treatment x family within position within species ($p = 0.008$) is largely explained by one bottomland bur oak family (HW11B) that put on greater than 3 mm of new diameter growth on more than 75 percent of its seedlings that were flooded. At the end of the study, differences ($p < 0.001$) existed in seedling basal stem diameters among families within all positions within species (Walsh 2007).

At the end of the growing season, seedling root and stem dry weight, but not leaf dry weight, had a highly significant flood x species interaction ($p = 0.012$, <0.001, and $= 0.692$, respectively). Root and stem dry weights of swamp white seedlings were less affected by duration of flooding than were root and shoot dry weight of white oak and bur seedlings, both of which showed marked declines with increasing duration of flooding (Fig. 3). Mean root dry weight of white oak seedlings inundated for 8 weeks was less than that for the seedlings destructively sampled when flood treatments were initiated (3.6 versus 5.0 g, respectively). Tang and Kozlowski (1982) also found partial inundation of 4-week-old bur oak seedlings for 4 weeks reduced plant dry weight, especially root dry weight.

A flood x position within species effect was not found for root, stem, or leaf biomass ($p = 0.177$, 0.276, and 0.224, respectively); however, a position within species was found for these variables ($p <0.001$, <0.001, and $= 0.009$, respectively). As was found with the variables described earlier, root biomass and stem biomass of white oak seedlings from upland seed sources were larger than those of seedlings from bottomland sources (Fig. 3). For bur oak, the position within species effect was most evident for root biomass, where seedlings from bottomland seed sources had larger root biomass compared to seedlings from upland seed sources. With swamp white oak, there was no pronounced position within species effect for root, stem, or leaf biomass.

DISCUSSION AND CONCLUSIONS

Percent seedling survival was high for all three oak species treated with 0, 4, and 8 weeks of partial inundation of container-grown seedlings in a well drained soil-less potting mix. Based on previous results with bare-root white oak seedlings in riparian soils (Kabrick and others 2007), we expected few if any white oak seedlings would survive 8 weeks in water-saturated soils. In this study, we did not measure dissolved oxygen within the stagnant flood water or redox potential of the soil-less potting mix; however, in a separate laboratory study, the redox potential after 1 week of flooding was higher in the soil-less potting mix than in the riparian topsoil taken from the Flood Tolerance Laboratory (150 to 200 versus 50 to 100 mV, respectively). Likewise, dissolved oxygen measured near the surface of the soil-less potting medium averaged 60 to 80 percent, compared to less than 5 percent in riparian topsoil. Several factors besides the potting mix may have contributed to a higher than expected dissolved oxygen content. The frequent replenishing of stagnant flood waters using water under pressure may have also helped replenish dissolved oxygen. Because studies were done in a shade house, flooded tanks were also exposed to rain events, which have also been shown to replenish dissolved oxygen (Broadfoot 1967, Van Sambeek and others 2007). Finally, the shade cloth covering the shade house kept flood waters cooler than had been found with exposed stock tanks and may have reduced oxygen demand for root respiration.

Several observations confirm that the flood treatments were effective. Although less than half of the seedlings grew a third flush after flood treatments were initiated, flooding did decrease numbers of seedlings that flushed when flooded or during post-flood recovery. Flooded seedlings of bur and swamp white oak produced greater basal diameter growth than the control seedlings. Gardiner and others (1993) also reported greater basal diameter growth on two of four southern oak species when partially inundated. No studies were done to determine if the increased basal diameter growth for flooded bur and swamp white oak seedlings was due to increased production of xylem, hypertrophied lenticels, or aerenchyma; however, Gardiner (2001) indicated southern bottomland oaks, including white oak, do not appear to be equipped to develop aerenchyma tissue. Although no seedlings produced adventitious roots, flooded seedlings of all three species produced hypertrophied lenticels. Tang and Kozlowski (1982) reported both hypertrophied

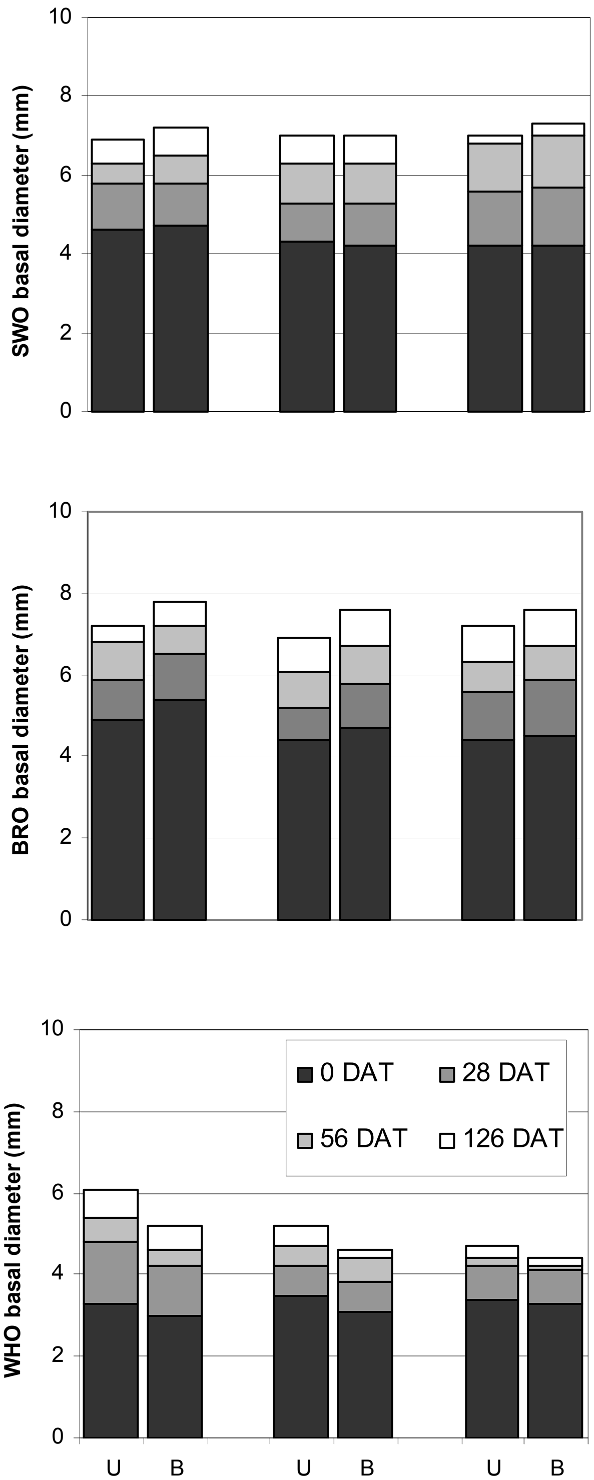

Figure 2.—Seedling basal diameter for white (WHO), bur (BRO), and swamp white oak (SWO) produced from upland (U) and bottomland (B) acorn sources 0, 28, 56, and 126 days after initiation of flooding (DAT) for 0, 4, and 8 weeks.

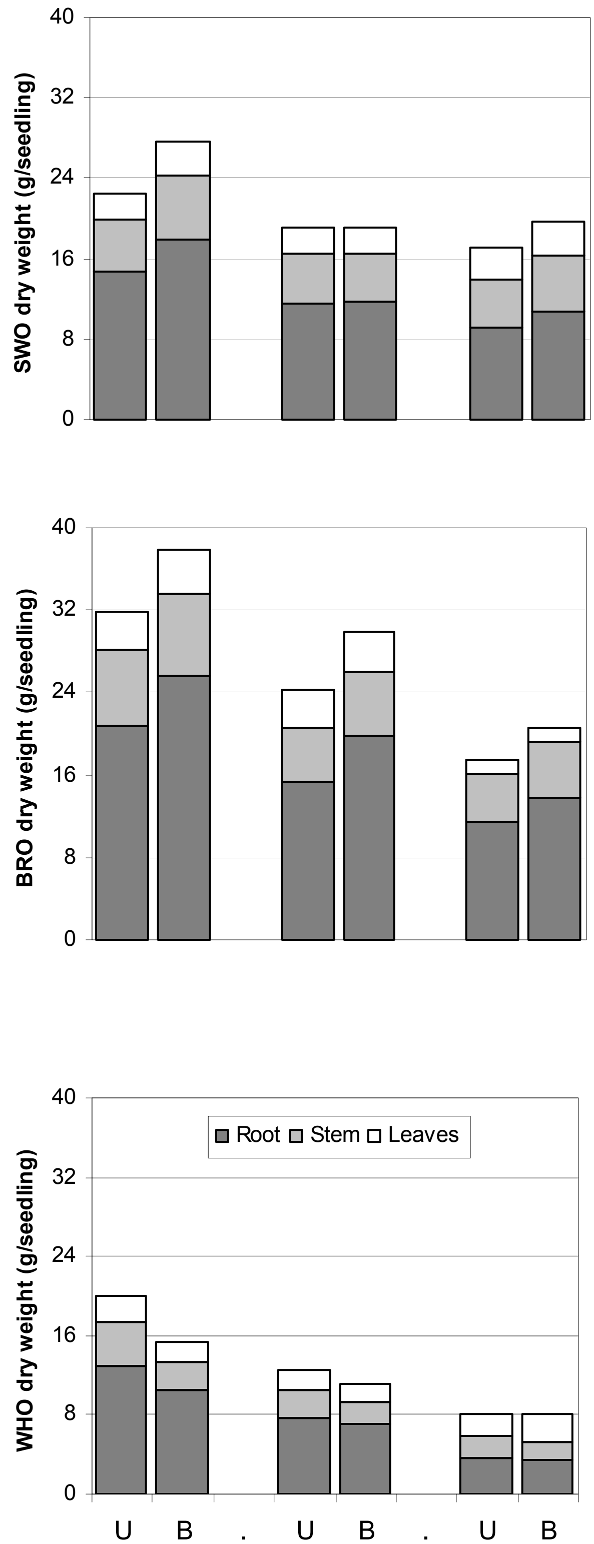

Figure 3.—Mean seedling root, stem, and leaf dry weight for white, bur, and swamp white oak grown from upland and bottomland acorn sources and flooded in mid-season for 0, 4, or 8 weeks.

lenticels and adventitious roots on bur oak seedlings flooded for 4 weeks. In addition, seedling root biomass at the end of the growing season for white oak flooded for 8 weeks was less than that for white oak seedlings when flood treatments were initiated.

Basal diameter growth and seedling biomass for white oak declined with increasing flood duration. In contrast, seedling growth and biomass of swamp white oak were largely unaffected by 4 or 8 weeks of partial inundation. For bur oak seedlings, basal diameter was largely unaffected; however, new shoot growth and biomass decreased with increasing flood duration. The relative rankings for flood tolerance of swamp white oak > bur oak > white oak in our study is similar to that reported by Kabrick and Dey (2001), but is not supported by the species rankings reported earlier by Bell and Johnson (1974), Whitlow and Harris (1979), or Allen and others (2001).

All three species had highly significant differences among families within position within species for most variables, suggesting excellent opportunities exist for selection and genetic improvement for flood tolerance. Results also suggest collection of acorns from bottomland stands of bur and swamp white oak are likely to produce better seedlings for bottomland restorations than seedlings from acorns collected from upland stands.

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CROP TREE RELEASE INCREASES GROWTH OF RED OAK SAWTIMBER IN SOUTHERN NEW ENGLAND: 12-YEAR RESULTS

Jeffrey S. Ward[1]

Abstract.—In winter 1995, five crop tree thinning plots were established in central Connecticut. Stands were mature red oak sawtimber (74-94 years old) with no history of prior management. Crop trees were upper canopy red oaks (northern red, black, and scarlet) with a potential grade 1 or 2 butt log. Growth of crop trees was monitored for the next 12 years. Diameter, cubic-foot, and board-foot growth was increased by release on three or four sides (complete release). This increase was maintained for at least 12 years. Mean diameter growth 0-3 years after cutting was slightly greater, 18 percent, for completely released trees than for unreleased trees. For the 4-6, 7-9, and 10-12 year periods after cutting, diameter growth of completely released trees was greater than for unreleased trees: 47, 41, and 42 percent, respectively. Cubic-foot and board-foot growth were greater for completely released than unreleased trees. Annual volume growth (cubic-foot) increases ranged from 50 percent for trees with diameters 10.1-11.9 inches to 29 percent for trees larger than 16.0 inches. For sawtimber oak stands where maintaining high forest cover and noncommodity attributes are important considerations, crop tree management should be considered.

INTRODUCTION

The 28 million acres of sawtimber oak-hickory forest in the Northeast and North Central states (Smith and others 2004) have become economically valuable assets. Family forest owners control the majority of forest land in the northern United States (Butler and Leatherberry 2004). Many of these holdings, especially those less than 50 acres, are managed for noncommodity amenities such as aesthetics, privacy, and wildlife (Butler and Leatherberry 2004). Nevertheless, forest ownership incurs expenses such as real estate taxes, insurance, and protection. Family forest owners may consider forest management practices, such as crop tree management, that both retain the noncommodity amenities and provide a source of income.

The current public bias against even-aged management has resulted in an increased proportion of public and private forests being managed through partial cuts over longer rotations. Partial cuttings on private lands are all too often high-grading operations under the guise of "selective" harvesting (Nyland 1992). Improperly applied partial cutting can accelerate the conversion of oak stands to mixtures of maple, birch, and other species with lower commercial and wildlife values (Abrams and Scott 1989, Ward 2005). For larger public forests and smaller private parcels where even-aged management is not possible, crop tree management could provide a viable alternative management practice that maintains forest productivity.

Previous crop tree research has largely focused on release of saplings (Della-Bianca 1975, Lamson and Smith 1978, Ward 1995) or poles (Dale and Sonderman 1984, Mitchell and others 1988, Miller 2000, Schuler 2006). There have been few studies on releasing mature (>80-yr-old) oaks, in part because of an earlier perception that mature trees in unthinned stands do not respond to thinning (Sander 1977, Hibbs and Bentley 1983, Dale and Hilt 1989). More recent reports suggest that diameter growth of sawtimber oaks can be increased by high thinning without a loss of quality. Studies in Kentucky (Miller and Stringer

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2004), West Virginia (Smith and others 1989), North Carolina (Beck 1987), and Arkansas (Graney 1998) have reported that diameter growth of sawtimber oak increases following crop tree release.

OBJECTIVES

The objective of this study was to determine if crop tree management would increase diameter and volume growth of mature oak sawtimber for at least 12 years. These results will provide information for foresters considering crop tree management in sawtimber oak stands where initiating regeneration harvests is not currently feasible. Crop tree management would maintain many of the noncommodity amenities desired by forest owners and simultaneously provide a source of revenue.

STUDY AREAS

Four crop tree plots (Bear Pole, China Pole, Bear Saw, Rocky Saw) were established on Northeast Utility Forest Management Lands in cooperation with Ferrucci and Walicki, LLC, in 1995. A fifth plot (Larkin Saw) was established on private land in 1995. All plots were in mature upland oak forests (74 to 94 years old) in central Connecticut that had not been previously thinned and were scheduled for timber stand improvement. Plots were fully stocked with pre-release basal area values that averaged 88 to 113 ft^2/acre for trees with diameters greater than 4 inches. The Bear Pole and China Pole plots were near ridge tops and had low site indices of 48-50. The other plots were on benches or flats and had site indices that ranged from 55-62. For crop trees, median initial diameter was 12.6 inches (range of 6.0-26.0 inches) and median initial height was 67 feet (range of 44 to 96 feet). Sawtimber trees had a median sawlog length of 35 feet with 157 board-feet (International ¼ rule). Additional details on initial plot and tree characteristics can be found in Ward (2002).

METHODS

Sixty crop trees were selected at each plot (300 trees total). Selection criteria for crop trees were codominant or dominant crown class, at least 17 ft to first fork, and a potential grade 1 or 2 butt log. Composition of crop trees was northern red oak (*Quercus rubra*) 59 percent, black oak (*Q. velutina*) 39 percent, and scarlet oak (*Q. coccinea*) 2 percent. Trees were systematically numbered and split into two groups: trees 1-30 and trees 31-60. Treatment (crop tree release) was randomly assigned to one group on each plot. Release was completed as part of a commercial thinning operation on all plots during 1995. Most of the remaining trees that competed with selected crop trees (crowns within 3 feet of crop tree crown) were either felled or girdled. Some competing trees not removed during thinning on the China Pole plot were girdled in early summer 1996.

Crop trees were banded at 4.5 feet and numbered with red paint. Diameters were recorded to the nearest 0.04 inches each year during the dormant season. The amount of release for each crop tree was assessed in 25-percent increments 1 year after plot establishment. Total height and pulp height (4-inch top) were recorded to the nearest foot for all trees. Sawlog height (9-inch top) was recorded to the nearest foot for all trees with a diameter greater than 10.5 inches.

Trees were split into five size classes by diameter for analysis: medium poles (<10.0 inches), large poles (10.0-11.9 inches), small sawtimber (12.0-13.9 inches), medium sawtimber (14.0-15.9 inches), and large sawtimber (>16.0 inches). Cubic-foot volumes were determined using formulas from Marquis (1977). Board-foot volumes (International ¼ rule) were calculated using Scrivani (1989) with form class 78. The Scrivani algorithm was modified for sawlog length. For each size class, the effect of treatment on annual

Table 1.—Annual diameter (inches), cubic-foot volume, and board-foot volume (International ¼ rule) growth of released and control crop trees in southern New England sawtimber oak stands. Crop trees were released during 1995

d.b.h.	Released		Control				
(inches)	Mean (SE)	N	Mean (SE)	N	F-ratio	df	Prob
			--------------Annual diameter growth (1995-2006)-------------				
<10.0	0.24 (0.02)	19	0.16 (0.02)	38	23.7	1	0.000
10.0 - 11.9	0.24 (0.01)	26	0.17 (0.01)	36	27.3	1	0.000
12.0 - 13.9	0.24 (0.01)	48	0.17 (0.01)	44	40.2	1	0.000
14.0 - 15.9	0.24 (0.01)	24	0.19 (0.02)	18	7.3	1	0.011
>16.0	0.29 (0.02)	19	0.23 (0.01)	23	13.5	1	0.001
			------------Annual cubic-foot growth (1995-2006)-------------				
<10.0	0.8 (0.08)	19	0.5 (0.08)	38	22.3	1	0.000
10.0 - 11.9	1.0 (0.06)	26	0.7 (0.06)	36	28.2	1	0.000
12.0 - 13.9	1.1 (0.04)	48	0.8 (0.04)	44	25.6	1	0.000
14.0 - 15.9	1.3 (0.09)	24	1.0 (0.10)	18	5.2	1	0.029
>16.0	2.1 (0.15)	19	1.6 (0.12)	23	8.4	1	0.006
			-------------Annual board-foot growth (1995-2006)------------				
<10.0	-	-	-	-	-	-	-
10.0 - 11.9	4.5 (0.41)	14	3.3 (0.39)	17	7.0	1	0.014
12.0 - 13.9	5.5 (0.23)	48	4.3 (0.24)	44	14.5	1	0.000
14.0 - 15.9	6.7 (0.48)	24	5.4 (0.57)	18	3.6	1	0.067
>16.0	11.3 (0.88)	19	8.8 (0.70)	23	7.4	1	0.010

diameter, cubic-foot, and board-foot growth was determined using a two-factor ANOVA (plot, treatment). Tukey's HSD test was used to test differences of tree growth among release levels. Differences were judged significant at $p < 0.05$.

RESULTS AND DISCUSSION

Diameter Growth after Release

Crop tree release increased diameter growth of oaks in all diameter classes examined (Table 1). Growth increases for the 12-year period ranged from 52 to 26 percent for trees with diameters less than 10.0 inches and 14.0-15.9 inches, respectively. During the 12-year period, diameter growth of completely released crop trees was 0.24 inches/year, compared with 0.17 inches/year for unreleased trees, a difference of nearly 0.07 inches/year. In other words, 13 years after treatment, completely released trees will gain an extra inch in diameter relative to unreleased trees. This growth is similar to the growth responses observed for 54-year-old red oaks in West Virginia (Lamson and others 1990), 61-year-old red oaks in Arkansas (Graney 1998), 75- to 80-year-old red oaks in West Virginia (Smith and others 1989, Smith and Miller 1991), and 70- to 75-year-old white oaks in Kentucky (Miller and Stringer 2004).

An earlier assessment of this study noted that there was a delay in growth response of previously unmanaged oaks to crop tree release (Ward 2002). Relative to unreleased controls, crop tree release increased diameter growth of sawtimber oaks by less than 20 percent for the first years after treatment (Fig. 1). Other studies have also reported a delayed growth response for sawtimber red oaks (Graney 1998,

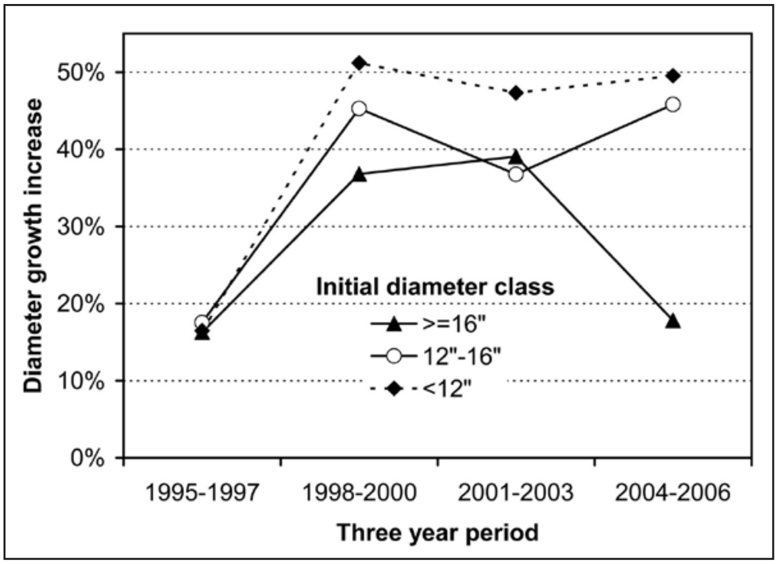

Figure 1.—Diameter growth (percent) of released (two or more sides) relative to control (not released) oak trees by initial diameter class for the first 12 years after treatment in southern New England.

Meadows 1998). However, diameter growth of 85-year-old oaks increased immediately after release in North Carolina (Beck 1987).

This study found no evidence that the growth of released crop trees, relative to control trees, had slowed 12 years after release, except for trees with initial diameters greater than 16 inches (Fig. 1). Diameter growth of released crop trees was greater than for unreleased trees during the subsequent three 3-year periods for trees smaller than 16 inches. Released trees grew 47 percent more than unreleased trees 4 to 6 years after release, 41 percent more 7 to 9 years after release, and 42 percent more 10 to 12 years after release. Extended periods (>10 years) of increased growth for sawtimber-sized oaks after release have been reported elsewhere (Sonderman 1984, Beck 1987, Graney 1998, Perkey and Onken 2000).

Degree of Release

Discounting growth during the first 3 years after release, when there was a minimal growth response (Fig. 1), the increase in diameter growth was directly related to the amount of release for trees released on two or more sides (Fig. 2). Diameter growth of trees released on one side was not significantly different from that of unreleased trees ($p > 0.99$). Releasing trees on two sides increased diameter growth during the

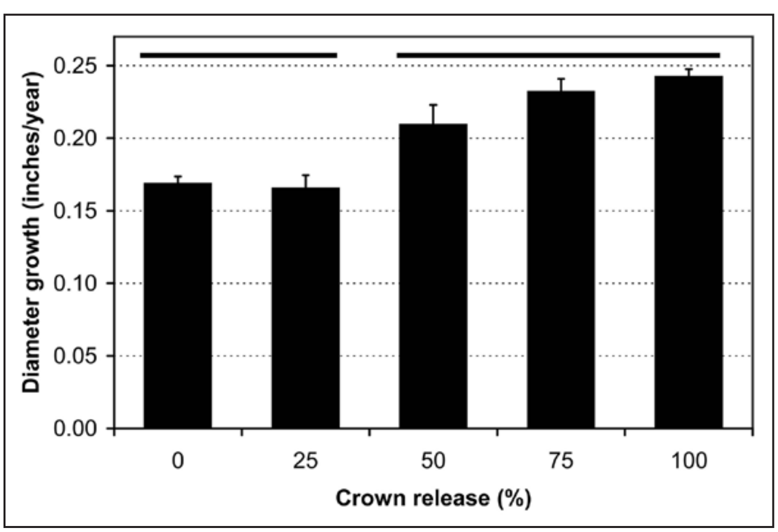

Figure 2.—Annual diameter growth (standard error) by amount of crown release in a sawtimber oak crop tree study in southern New England. Growth is for the period 4-12 years after initial treatment. Release levels linked by horizontal lines above bars were not found significantly different using Tukey's HSD test ($p < 0.05$).

fourth through sixth years after release by 25 percent relative to unreleased trees. Releasing trees on three sides increased diameter growth by another 15 percent, whereas complete release increased growth by an additional 16 percent.

Early studies reported diameter growth was not significantly increased by releasing only one side (Lamson and others 1990). Releasing red oaks on two or more sides did increase diameter growth relative to unreleased trees in other studies (Lamson and others 1990, Graney 1998, Perkey and Onken 2000). Similarly, release on two or more sides was required before there was an increase in diameter of black cherry (Smith and others 1994).

As noted in the earlier report (Ward 2002), only minimal growth response occurred when less than two sides were released (Lamson and others 1990, Smith and others 1994; Fig. 2). This may explain, in part, earlier recommendations not to thin mature sawtimber stands (Sander 1977, Hibbs and Bentley 1983, Dale and Hilt 1989). Most prior thinning studies in sawtimber stands were area-wide, low thinnings. Low thinning, with its emphasis on removing smaller trees, would not release residual sawtimber trees sufficiently (two or more sides) to initiate a positive growth response.

Volume Growth

It is important that any management alternative not sacrifice potential economic returns on forests that are actively managed for timber. For most diameter classes, cubic-foot and board-foot volume growth of completely released crop trees was higher than for unreleased trees (Table 1). For example, crop tree release increased volume growth of trees with diameters greater than 16 inches by 29 percent (Fig. 3).

Because several assumptions were made in estimating board-foot volume growth, estimates of volume change probably underestimated the true magnitude of the increases in economic value. First, it was assumed that sawlog height did not change. Second, no premium in price given for larger diameter logs (i.e., higher prices paid for higher grades were not factored into increased value). No increase in value was given to larger diameter trees because of regional and temporal vagrancies given for higher log grades.

There is little published information on volume growth of individual trees following crop tree release. However, thinning studies indicate that diameter growth of residual trees is maintained for at least 10 years (Sonderman 1984, Stringer and others 1988, Graney 1998). Stand volume growth was higher on thinned than control plots in West Virginia (Smith and Miller 1987). Initial gains in stand volume growth following complete release are maintained for at least 14-17 years (Ward 2005). After 32 years, black and scarlet oak volumes were higher on thinned than control plots (Dwyer and Lowell 1988).

CONCLUSIONS

This study found complete release of sawtimber red oak crop trees resulted in significant and sustained increases in diameter and volume growth (Table 1, Fig. 1). The combination of the positive growth response of crop trees and the aesthetic appeal of the residual stand (pers. obs.), suggests that crop tree management may be a potential introduction to forest management for forest owners who are hesitant to initiate harvesting, or for those for whom high forest cover and noncommodity attributes are primary considerations. The results indicate that the upper age limit at which red oaks respond to high thinning is at least 90 years and initiation of regeneration treatments can be delayed in some regions. Therefore, crop tree management could also be used on larger tracts where development of stands with a balanced age structure would require that the regeneration cuts in some stands be delayed past economic maturity.

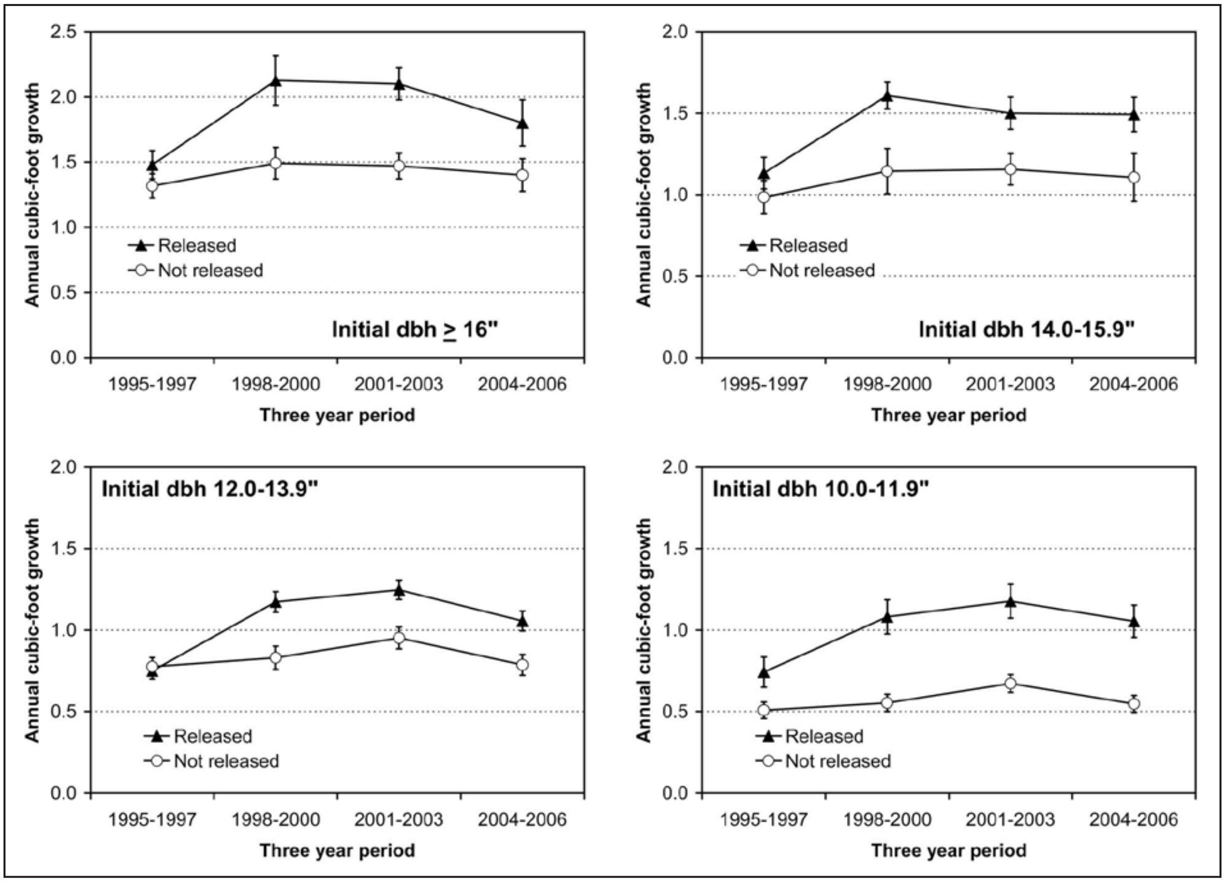

Figure 3.—Cubic-foot volume growth of released (two or more sides) relative to control (not released) oak trees by initial diameter class and 3-year intervals for the 12 years after treatment in southern New England.

ACKNOWLEDGMENTS

A special thanks to Northeast Utilities, Ferrucci and Walicki, LLC, and Dr. Charles Larkin, who donated the land, materials, and personnel that made this research possible. J.P. Barsky assisted with the data collection and plot maintenance. This research was partly funded by McIntire-Stennis Project CONH-554.

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SPECIES COMPOSITION, DIAMETER DISTRIBUTION, AND CROWN CLASS AT INITIATION OF A THINNING STUDY OF POLE-SIZE HARDWOOD STANDS IN THE HOOSIER NATIONAL FOREST

Ryan L. Woods and Douglass F. Jacobs[1]

Abstract.—During the spring of 2007, a low thinning was implemented in stands on the Hoosier National Forest that had been clearcut harvested between 1975 and 1979; treatments consisted of 60- and 75-percent residual stocking, as well as control plots with no thinning. The 60-percent treatment increased the relative oak density per acre in all stands with the exception of one stand that contained no oak component prior to thinning. The 75-percent stocking treatment resulted in only marginal increases in relative oak density. Relative density increases for yellow-poplar and black cherry were greater in 60-percent treatment plots than in 75. Conversely, 75-percent treatment plots had nearly twice the relative density of other hardwoods compared to that of the 60-percent plots. Mean diameter distribution in the 60-percent plots showed a more pronounced increase in diameter than that of the 75-percent plots. These preliminary differences resulted from a greater stocking removal of stems in the lower crown and diameter classes in the 60-percent treatment plots.

INTRODUCTION

Mid- to late-successional, shade intolerant species such as oaks (*Quercus* spp.) are an integral component to the ecology and economy in many areas of the Central Hardwood Forest Region. They have proven difficult to regenerate and maintain without proper silvicultural management. It has been well documented that even-aged management is the preferred and most successful method of regenerating intolerant species (Johnson and others 2002). However, these methods often fail to achieve adequate oak regeneration without additional intermediate treatments (Abrams and Nowacki 1992, Jenkins and Parker 1998, Johnson and others 2002).

The success of even-aged silvicultural methods in regenerating oaks is frequently limited to the stem initiation stage. During the stem exclusion phase, however, oaks are relatively low in number compared to early successional species, such as yellow-poplar (*Liriodendro tulipifera* L.) (Fischer 1987, Brashears and others 2004) and black cherry (*Prunus serotina* Ehrh.) (Schuler 2006). Even-aged regeneration methods produce a high number of stems per unit area, which results in increased competition among stems, slower growth rates, suppressed stems, and eventually mortality (Oliver and Larson 1996). Species such as yellow-poplar and black cherry are especially problematic because of their ability to exploit available growing space through rapid growth and subsequently suppress slower-growing species like oaks (Schuler 2006). This process can delay economic maturity, as well as be ecologically detrimental to a stand as undesirable species are established. A common silvicultural prescription to mitigate these effects is thinning.

Thinning regimes may help to increase stand productivity and value, attain desirable species composition, and select future crop trees. Thinning serves to allocate a greater amount of growing space to fewer stems through the removal of others (Johnson and others 2002). The reduction in competition produces favorable growing conditions for residual trees by increasing available sunlight (Hale 2001), soil moisture

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(Concilio and others 2005, McCarthy and Brown 2006), and nutrients (Thibodeau and others 2000). Studies have shown thinning can increase diameter growth of residual trees at various stages of stand development. For example, Lamson and Smith (1978) reported diameter increases in stands 9 years of age and Nowak and Marquis (1997) found increased diameter growth in mature stands 70 years of age as a result of thinning. Additionally, Gingrich (1970) showed that board-foot volume yield in upland central hardwood stands could be doubled by thinning stands early and frequently throughout their development compared to unthinned stands. Thinning also provides an opportunity to improve stand structure in terms of species composition and diameter distribution. Harvesting undesirable species and stems with poor vigor or form can increase the proportion of desirable species and crop trees.

Although stand productivity may increase as a result of allocating additional growing space to fewer trees, there are several potential risks. Excessive thinning could jeopardize wood quality (Dale and Sonderman 1984), increase the chance of windthrow, or promote vigorous growth of understory vegetation, thereby inadvertently increasing competition for site resources (Smith and others 1997). Conversely, removing too few stems may result in lost opportunity to improve growth rates, shorter period for re-entry, longer return of invested capital, and incomplete utilization of growing space (Daniel and others 1979, Johnson and others 2002).

Deciding upon the appropriate level of thinning is vital to achieving maximum board-foot volume yield. The challenge in determining the appropriate stand density is to provide an abundant amount of growing space without reducing total stand productivity or quality. Gingrich (1967) conducted an intensive study in predominately upland oak-hickory stands to develop a well defined range of stand densities that would maximize stand growth. Gingrich's stocking guide is based on the theory that growing space utilized by an individual tree is dependent on the size of the tree and its associated diameter and is intended to assist forest managers in determining appropriate silvicultural prescriptions given the current density of a stand. Gingrich (1967) identified A (overstocked), B (fully stocked), and C (understocked) levels of stocking; stands that have stocking below the C level are typically not deemed worth managing (Parker and Merritt 1995). Roach and Gingrich (1968) found that in stands with high initial stocking, such as clearcuts, reductions of stocking should be gradual in order to help ensure there is not a surplus of growing space and to reduce the likelihood of poor stem quality from epicormic branching.

OBJECTIVES

This paper reports baseline changes in species composition, diameter distribution, and crown class after thinning treatments were implemented to characterize the effects of density reductions. Hilt and Dale (1987) found that oak, yellow-poplar, and other hardwoods species comprised 10, 5, and 85 percent respectively of the 40 largest trees per acre in a 21-year-old even-aged central hardwood stand after implementing a free thinning to 50-percent residual stocking. They also found that oak, yellow-poplar, and other hardwood species comprised 17, 17, and 64 percent, respectively, of the 40 largest trees in a 21-year-old stand after thinning to 70 percent stocking. Both stocking levels showed an increase in the oak component compared to the control, which contained 6, 13, and 81 percent of oak, yellow-poplar, and other hardwood species, respectively. Dale and Sonderman (1984) conducted a free thinning in a 33-year-old predominantly white oak stand in Kentucky and found the relative density of dominant and codominant stems in stands with 60 and 45 square feet per acre of residual basal area to be 271 and 214 stems per acre, respectively, compared to 279 stems per acre in the control plots. Dale and Sonderman (1984) also observed an increase in quadratic mean diameter in each crown class as residual stocking decreased. These studies are examples of how thinning can directly improve stand structure and composition through initial changes in species composition and diameter distribution. However, they do not take into account the crown position of individual species (i.e., oaks, yellow-poplar, and black cherry), which has been shown to be critical to maintaining those species in the stand (Fischer 1987, Brashears and others 2004, Schuler 2006). Therefore, to better understand the effects of density reduction on short-term stand dynamics, the objective of this study is to characterize changes in stand structure, in particular reference to oaks, resulting from different levels of density reduction from low thinning.

STUDY AREA

This study was conducted in the Hoosier National Forest (HNF). The HNF is composed of upland hardwoods and is located in the unglaciated central portion of southern Indiana. The experimental sites of this study are located within the Tell City Management Unit; the area lies within the Crawford Upland subsection of the Shawnee Hills section of the Interior Low Plateau as defined by Homoya and others (1985). The topography of this region consists of numerous hills composed of acid silt loams of the Wellston-Zanesville-Berks association that were formed from sandstone-loess and marked by sandstone outcrops and rock shelters (Homoya and others 1985).

This study monitored five stands that were clearcut harvested between 1975 and 1979. Each stand was evaluated in the spring of 2006 and selected based on the criteria that they were a minimum of 20 acres in size, naturally regenerated following clearcut harvesting, free from large blowdown, insect or disease events, and had only infrequent occurrence of grapevines (*Vitis* spp. L.) in the regenerating stands. Stand density for these five stands ranged from approximately 725 stems per acre to 1,500 stems per acre and all stands were found to be at approximately 100-percent stocking. Species composition varied greatly, with the most common species being white oak (*Quercus alba* L.), yellow-poplar (*Liriodendro tulipifera* L.), black cherry (*Prunus serotina* Ehrh.), scarlet oak (*Quercus coccinea* Muenchh), and sugar maple (*Acer saccharum* Marsh.).

METHODS

In the fall of 2006, three relatively homogenous 1-acre treatment plots were located within each of the five stands with a 70-foot treatment buffer surrounding each treatment plot. Four permanent 0.1-acre subplots were installed within each of the 1-acre treatment plots. All stems 1 inch and greater in diameter at breast height (d.b.h.) were inventoried in each of the subplots prior to thinning; species, d.b.h., and crown class were recorded for each stem. Treatments were randomly assigned to plots at three levels of residual stocking, based on Gingrich's (1967) stocking guide for upland central hardwoods. Gingrich (1967) found that stands did not fully utilize the available growing space below the B level or below 57-percent stocking; therefore, it is not recommended to reduce stocking more than 40 percent in a stand that is near 100-percent stocking. The suggested minimum residual stocking level of 60 percent and moderate level of 75 percent were therefore the chosen treatments in this study.

Thinning from below, often referred to as low thinning, was used to achieve the desired stocking levels. This method has been shown to decrease the relative proportion of undesirable species or low quality stems, as well as to increase average tree size (Meadow 1993). The removal of the lower-class trees simulates an increased rate of natural mortality from self-thinning during the stem exclusion stage (Smith and others 1997) and results in allocating more growing space to larger-diameter trees. This method is preferred because it can be implemented with very little risk of reducing gross stand production (Smith and others 1997). Stems in the lower crown class are not preferred for release as they often do not recover from being

Table 1.—Number of stems per acre (n) and change in relative density (RD) per acre for dominant and codominant stems of four species groups in each treatment after thinning

Species group	Stocking	Stand 1 n	Stand 1 Change	Stand 2 n	Stand 2 Change	Stand 3 n	Stand 3 Change	Stand 4 n	Stand 4 Change	Stand 5 n	Stand 5 Change
Oak	100%	87	0%	68	0%	248	0%	10	0%	180	0%
	75%	115	7%	40	0%	198	4%	20	4%	173	0%
	60%	33	5%	95	11%	270	20%	0	0%	165	17%
Yellow-poplar	100%	33	0%	68	0%	0	0%	45	0%	18	0%
	75%	13	0%	3	-1%	0	0%	80	-3%	0	0%
	60%	35	3%	3	-1%	0	0%	30	8%	0	0%
Black cherry	100%	50	0%	90	0%	5	0%	133	0%	35	0%
	75%	23	-3%	70	-2%	18	-4%	15	1%	35	-2%
	60%	53	1%	38	4%	50	9%	18	5%	38	3%
Other hardwoods	100%	95	0%	328	0%	115	0%	78	0%	180	0%
	75%	100	-7%	200	-4%	43	0%	48	3%	223	0%
	60%	115	-8%	125	-15%	23	-29%	60	-14%	75	-20%

suppressed over long periods of high competition. However, stems in the upper canopy are likely more vigorous, of higher quality, and better suited for the site (Gingrich 1971).

The hierarchy for species favored as leave trees was based on the species' ecological and economic importance and the probability that it would be a component of the stand at the end of rotation. Dominant and codominant oaks were favored over dominant and codominant black cherry and yellow-poplar due to oaks' inability to successfully compete with the faster-growing species, such as black cherry and yellow-poplar, during the stem exclusion phase. One-acre treatment plots and associated buffers were thinned to designated stocking levels in spring, 2007. Each subplot was re-inventoried after thinning was completed. Changes in species composition, d.b.h, and crown class were evaluated by direct comparison of pre- and post-thinned subplots within each treatment, as well as between treatments.

RESULTS

The 60-percent residual stocked plots in four out of five stands showed an increase in the relative density (RD) per acre of oak stems in the dominant and codominant crown class (Table 1); the only stand that did not show an increase in oak was that which had no oak component prior to thinning. This increase in RD resulted in an increase of 54, 28, 10, 2, and 0 oak stems per acre in the main canopy. Sixty-percent residual stocked plots showed marginal changes in the RD of yellow-poplar. Only one stand showed a minor decrease in the RD of yellow-poplar, whereas stand four showed an eight percent increase. Unlike yellow-poplar, the RD of dominant and codominant black cherry increased in all five stands (1, 4, 9, 5, and 3 percent), the greatest increase (9 percent) was equivalent to only five more stems per acre in the main canopy. Dominant and codominant stems in the other hardwoods group showed a consistent and rather large decrease in RD compared to the other three groups.

In contrast to the 60-percent stocking treatment, there was little change in the RD of oak in the 75-percent stocked plots. Three of the five stands showed little increase in relative oak density and two showed no change at all (Table 1). Similarly, the RD of yellow-poplar decreased slightly in two stands and remained

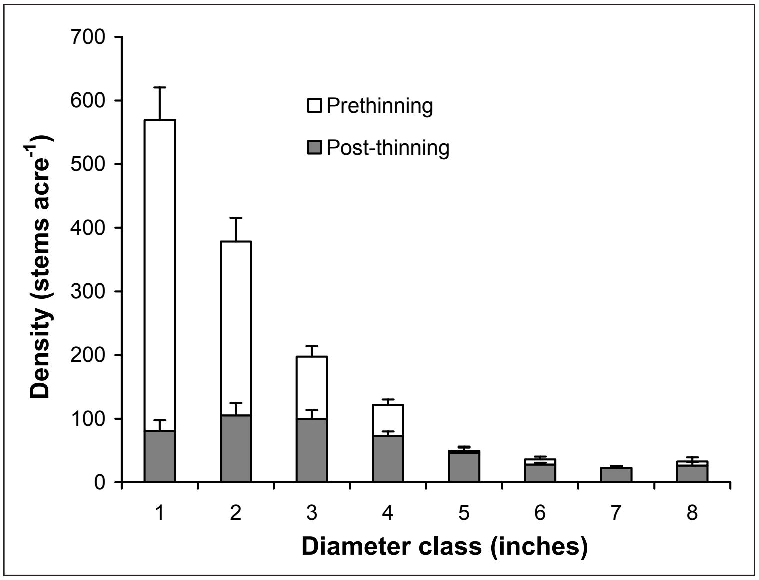

Figure 1.—Mean per acre diameter distribution of five stands for 60-percent stocked plots prethinning and post-thinning.

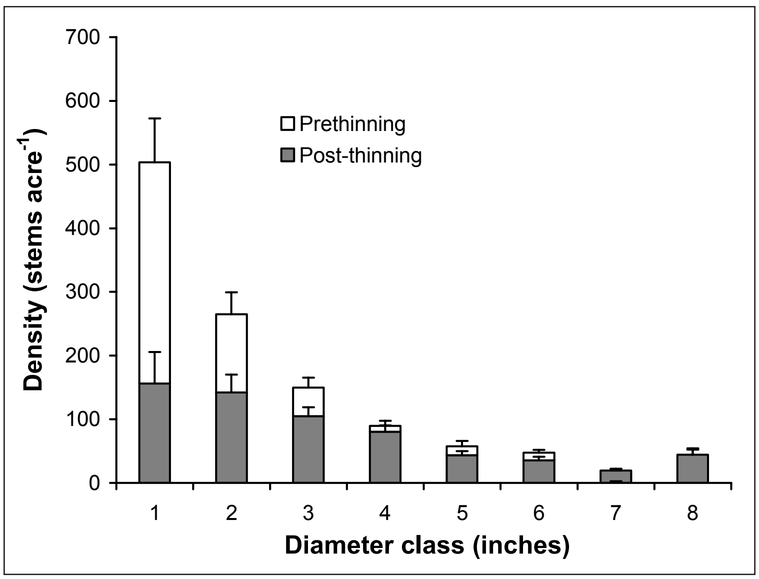

Figure 2.—Mean per acre diameter distribution of five stands for 75-percent stocked plots prethinning and post-thinning.

the same in another. Unlike the 60-percent stocking treatment, black cherry decreased in all but one stand, in which it increased by 1 percent. The large decrease in the other hardwoods group was not observed in the 75-percent stocking treatment as it was in the 60 percent.

The effect of thinning from below to obtain the desired stocking levels is apparent in the diameter distributions in Figures 1 and 2. An average of 912 stems per acre were removed from the 60-percent treatment plots; 96 percent of these stems were in the 1-, 2- , and 3-inch diameter classes (54, 31, and 11 percent, respectively). An average of 610 stems per acre were removed to achieve 75-percent stocking; the 1-, 2-, and 3-inch diameter classes comprised 90 percent of the removal; 60, 22, and 8 percent, respectively. The mean diameter distribution for 60-percent stocked plots (Fig. 1) showed a predominant shift from the typical reversed J-shaped curve to a more even distribution among diameter classes. The mean diameter distribution for the 75-percent stocked plots (Fig. 2), however, showed subtle changes and still resembles a reverse J-shaped curve.

DISCUSSION

Although the first thinning of a previously unthinned stand may produce the greatest intermediate yield (Gingrich 1971), it should be noted that these treatments were merely the beginning of a thinning schedule and that these stands should undergo subsequent thinning to further improve stand productivity and structure. Changes in species composition and diameter distribution from this initial thinning will influence the dynamics of these stands over the next 10 years as well as the subsequent thinning prescription.

The greatest impact on stand growth and structure through thinning can be made during the stem exclusion phase (Shifley 2004). Thinnings provide an opportunity to improve stand quality by changing species composition, improving tree spacing, and promoting the vigor of residual trees (Sonderman 1984, Gingrich 1970). A greater proportion of oaks in the upper canopy positions is especially important in maintaining the oak component in stands with highly competitive species like yellow-poplar and black cherry (Brashears and others 2004). This study demonstrates that the RD of dominant and codominant oaks can be maintained and even increased, by thinning from below (Table 1). Similar results were found by Hilt and Dale (1987), in which percentage of oaks in the largest 40 trees per acre increased as stocking decreased. The 75-percent stocked plots of stands two and five did not show an increase in the RD of oak as did the other three stands, and only marginal decreases of black cherry and other hardwoods were observed. Both the 60- and 75-percent treatments did not produce a large decrease in the highly competitive yellow-poplar and black cherry groups. This outcome indicates that residual stocking below 60 percent or an alternative thinning method may be needed to decrease those species' densities relative to oak. The more intense thinning could show reductions in yellow-poplar and black cherry similar to those observed in the hardwoods group between 75 and 60 percent stocking; the additional 15-percent stocking reduction resulted in large and consistent decreases in the hardwoods group. Shifley (2004) suggested that maintaining trees in the dominant and codominant canopy position is vital to increasing individual tree growth and stand productivity. Though the two treatments were able to at least sustain the RD of dominant and codominant oaks, it is unknown if these stems will be able to maintain their position. Schuler (2006) found that in 23-year-old stands of black cherry and northern red oak, a crown-touching release reduced the height growth of treated black cherry, while northern red oak was not affected. The crown-touching release allowed the northern red oak to gain a competitive advantage in height growth. The 60- and 75-percent stocking levels in this study may provide enough growing space to cause faster-growing species to allocate photosynthate for increased diameter growth and thus, reduce growth in height. This process could allow the slower-growing oaks an opportunity to increase their height and maintain or improve their canopy position.

As expected, thinning from below increased average stem diameter in both treatments (Figs. 1 and 2). The shift toward a larger diameter distribution was more pronounced in the 60 percent stocking treatments. While on average, a greater percentage of 1-inch diameter stems were removed from the 75-percent plots, the mean diameter distribution for 75-percent plots maintained the reverse J-shaped curve. As a result more growing space was allocated to larger-diameter trees in the 60-percent plots compared to that of the 75 percent. Dale and Sonderman (1984) found similar results as quadratic mean stem diameter increased for each crown class as residual stocking decreased. The additional 1- and 2-inch diameter stems in the 75-percent treatments suggest that the lighter thinning did not fully simulate the stem exclusion phase of stand development. However, Dale (1968) found that net basal area growth reached a maximum between 40 and 60 percent stocking in 25- to 35-year-old white oak stands in Kentucky and Iowa. He also concluded that net growth decreased at stocking above 60 percent due to natural mortality. Hilt (1979) observed little differences in periodic annual d.b.h. growth between medium (46-65 percent) and high stocking (66-80) levels in 23- to 34-year-old mixed oak stands. Conversely, Roach and Gingrich (1968) contend that with proper spacing, each tree has an adequate amount of growing space at the B stocking level (approximately 60 percent).

Dale (1968) reported that the majority of the growth response in 50-percent stocked plots of a 25-year-old Iowa stand and a 35-year-old Kentucky stand occurred by the second year after thinning and that growth was maintained through the third and fourth year. Dale (1968) also concluded that mean annual diameter growth of the largest white oak stems at 50 percent stocking showed 70- and 35-percent increase in the Iowa and Kentucky stands, respectively, compared to the largest white oaks in fully stocked stands over a 4-year period. Sonderman (1984) found diameter growth of yellow-poplar to be greater than that of oak in both 50 and 70 percent stocked plots 6 years after thinning a 29-year-old even-aged central hardwoods stand.

It is likely that most of the stand basal area growth (SBAG) and mean annual diameter growth (MADG) will occur in the first 4 to 5 years after thinning for both treatments. Treatment plots that contain a greater RD of yellow-poplar and perhaps black cherry will probably have greater increases in SBAG and MADG due to those species' ability to rapidly use available growing space. The greater growth increase will likely be more prevalent in the 60-percent treatments than in the 75 percent treatments. Whether the RD of dominant and codominant oaks will remain unchanged has not yet been determined. Previous studies found that oak height growth is competitive with black cherry height growth (Schuler 2006) but not that of yellow-poplar (Sonderman 1984).

These are baseline measurements of the first thinning in a series of thinnings that will be implemented in these stands at approximately 10-year intervals. This initial thinning has increased the oak component and increased mean diameter relative to the control. Therefore, it seems reasonable to assume there will continue to be a large oak component in these stands and that it can be enhanced in the next thinning treatment. In 10 years, each treatment plot will be near the A level or 100-percent stocking and ideal candidates for another thinning to further increase the oak component and mean diameter. Changes in the type of thinning and targeted residual species may be needed in future thinnings.

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FOREST HEALTH AND PROTECTION

FUNGI ASSOCIATED WITH STEM CANKERS AND COINCIDENTAL SCOLYTID BEETLES ON DECLINING HICKORY IN THE UPPER MIDWEST

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Abstract.—Higher than expected levels of hickory decline and mortality have recently been reported by Forest Health Monitoring, USDA Forest Service, on *Carya* spp. in Iowa, Maryland, Missouri, New York, Pennsylvania, and West Virginia. Widespread mortality of hickory has historically been attributed to outbreaks of the hickory bark beetle (*Scolytus quadrispinosus*) during extended periods of drought. Results of a preliminary survey conducted in Iowa, Minnesota, and Wisconsin during 2006 commonly found 1) a recently described fungus (*Ceratocystis smalleyi*) associated with bleeding spots and lesions on *Carya cordiformis*; 2) a fungus(*Fusarium solani*) with no known report of causing cankers on Carya species isolated from sunken, annual cankers; and 3) the fungi (*Phomopsis* spp.), which are commonly cited as the cause of Phomopsis stem and branch galls. We hypothesize that hickory mortality in these states is due to a decline complex of interacting predisposing, triggering, and contributing factors whose biotic agents are interchangeable.

INTRODUCTION

Hickories (*Carya* spp.) are an important component of many forest associations in the eastern United States, particularly various oak-hickory cover types. Bitternut hickory (*C. cordiformis*) is considered the most abundant and uniformly distributed of the hickories within this range (Smith 2004). It is an associated species in the sugar maple-basswood (Society of American Foresters Type 26; Eyre 1980) and sugar maple (Type 27) forest types of the northern forest region and the white oak-black oak–northern red oak (Type 52) and white oak (Type 53) in the central forest region.

Hickories are an important source of hard mast for wildlife and have the potential to produce valuable timber (Smith 2004). They are also important in the biological diversity of stands threatened by numerous other stressors and damaging agents. The high calcium content of the foliage of bitternut hickory is desirable for its ability to improve soils in the stands in which it grows (Smith 2004). Furthermore, the dense root system of the species contributes to good soil stability.

Severe decline and mortality of hickory have recently been reported in parts of the North Central and Northeastern Regions of the United States and in southern Ontario, Canada (USDA Forest Service 2004, Tucker and others 2006). Hickory decline, particularly of bitternut hickory and, to a lesser extent, shagbark has recently been noted in Iowa (Johnson and others 2005), in Missouri, Maryland, New York, Pennsylvania, and West Virginia by USDA Forest Service Forest Health Monitoring Program surveys (USDA Forest Service 2004), and in Wisconsin (Wisconsin DNR 2005). Widespread mortality of hickory has historically been attributed to outbreaks of the hickory bark beetle (*Scolytus quadrispinosus*)(Coleoptera: Scolytidae) during extended periods of drought (USDA Forest Service 1985). This insect is considered the

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Table 1.—Locations and stand characteristics of study sites for preliminary survey of selected stem damaging fungi and insects of declining hickory

County	Site	Stand Area (Acres)	Composition in Hickory (%)	Hickory in Decline (%)	Principal Hickory Species
		----------Iowa----------			
Buchanan	Coggon	20-100	50-75	30-75	Bitternut
Clayton	Elkport	20-100	10-25	10-30	Bitternut
Allamakee	Elon	5-20	50-75	30-75	Bitternut
		--------Minnesota----------			
Olmsted	Plainview	20-100	10-25	30-75	Bitternut
Olmsted	St. Charles	5-20	25-50	>75	Bitternut
		-----------Wisconsin----------			
Calumet	Chilton	20-100	10-25	>75	Bitternut (only)
Dane	Mt. Horeb	20	10-25	10-30	Bitternut
Dane	Dane	<5	10-25	10-30	Shagbark
Grant	Lancaster	5-20	<10	30-75	Bitternut
Shawano	Shepley	20-100	10-25	30-75	Bitternut
Monroe	Melvina	20-100	>75	10-30	Shagbark
Marathon	Rosholt	20-100	<10	30-75	Bitternut
Wood	Babcock	20-100	10-25	>75	Bitternut (only)

most important pest of hickories (Solomon and Payne 1986). Past land use and soil fertility were shown to indirectly determine outbreaks of the bark beetle (Dale and others 1990). In 1994, a newly discovered fungus was reported in discolored wood and sunken bark cankers associated with hickory bark beetle attacks (USDA Forest Service 1994). This fungus (*Ceratocystis smalleyi*) and a sister species (*C. caryae*) were recently described (Johnson and others 2005). Both species were pathogenic on 2-yr-old *Carya* spp. in greenhouse studies. The researchers suggested that *C. smalleyi* might play a significant role in hickory mortality. *Phomopsis* galls, *Armillaria* root rot, and a flat-headed woodborer (*Agrilus otiosus*) have also been associated with declining trees (Wisconsin DNR 2005). A re-examination of affected ecosystems is needed to determine and/or clarify the importance of hickory decline and mortality in relation to these damaging agents as well as in relation to climatic, edaphic, and cultural factors.

During 2006, we conducted a preliminary survey of hickory in Iowa, Minnesota, and Wisconsin in cooperation with state forest health specialists to look for the presence of stem-damaging cankers/galls on declining trees, isolate for organisms from affected tissues, and note presence of any xylem- or bark- feeding beetles associated with the stem-damaged trees. Results of that effort are reported here.

STUDY AREAS

Candidate stands with declining hickory were identified by forest health specialists and district foresters from the respective Departments of Natural Resources for Iowa, Minnesota, and Wisconsin. In general, forest stands of 20 to 100 acres with quite variable levels of hickory stocking were sampled (Table 1). The number of stands sampled per state was: Iowa, 3; Minnesota, 2; and Wisconsin, 8.

METHODS

Sample Collection

Only declining hickories were examined for stem damage and cankers. Signs of stem cankers/galls and/or insect activity on the stems of the selected declining trees were recorded. A small hand axe was used to cut through the bark into the sapwood to determine whether the lesion/canker or insect activity was superficial or penetrated to the cambium and sapwood. When penetrating cankers and/or insect damage was found, the outer portion of the stem area was removed with a small sledge hammer and hand axe. Stem samples were wrapped in dry paper towels, placed in polyethylene bags, and kept on ice during transport. The samples were subsequently stored at 36 °F until further processed in the USDA Forest Service laboratory in St. Paul, MN.

Sample Processing

In the laboratory, each sample was carefully examined and any visual damage observed (e.g., diffuse canker, annual canker, xylem discoloration, size and shape of insect boring holes, and pattern and relative size of any insect galleries) was recorded. Presence of any insects and their life stages were also recorded. Three methods were used to isolate fungi associated with the affected tissue. For the Iowa sites, wood chips from the margin between discolored and healthy wood were placed between two carrot disks and stored in plastic bags at 68 °F; isolation was subsequently attempted from any suspect carrot tissue (per Moller and DeVay 1968). Wood chips from the margin between discolored and healthy wood were also plated on lactic acid-amended potato dextrose agar (APDA) and on 2 percent malt yeast extract agar amended with 100 ppm streptomycin sulfate (MYEA+SS). Due to early difficulty in isolating *Ceratocystis*-like species, a third method was adopted for Minnesota and Wisconsin samples, which replaced the carrot disk method. Small cubes of discolored sapwood associated with bark cankers were placed in small moist chambers for 10 days. Ascospore masses produced by perithecia sporulating on the cubes were plated onto MYEA+SS.

Identification of Fungi

Pure cultures were obtained for the isolated fungi. The most prevalent isolate types were identified to genus and stored on agar slants at 36 °F. Morphological characteristics of the *Ceratocystis* isolates were compared to reference cultures of *C. smalleyi* and *C. caryae* obtained from T.C. Harrington, Iowa State University. For six of the *Ceratocystis* isolates, DNA was extracted, and sequencing of the internal transcribed spacer region of rDNA (ITS1 and ITS4) was completed. The sequences obtained were compared to those in GenBank using BLASTn search. Single spore cultures were derived from all *Fusarium* spp. isolates obtained. Morphological characteristics were used to identify the isolates to species (Booth 1971, Nelson and others 1983). DNA was extracted from 12 *Fusarium* isolates and sequencing of the internal transcribed spacer region of rDNA was completed using ef1 and ef2 primers. Because morphological and cultural characters are insufficient for identifying *Phomopsis* to species, we relied on the host association for a tentative identification. However, DNA sequencing was also completed for two isolates using nuclear ribosomal DNA internal transcribed spacer sequences (ITS1 and ITS2) per protocol of Murali and others (2006).

RESULTS

Types of Stem Damage/Cankers Sampled

Hickories, primarily bitternut, of all sizes were found with decline symptoms. Individual tree symptoms and stem/branch damage were highly variable; no single type of damage was found on most trees. For hickory saplings (<5 inches diameter at breast height [d.b.h.]), the tree crown and stem conditions observed included: 1) crown dieback—elongate, swollen, rough-bark canker; or 2) crown dieback—small leaves;

Table 2.—Frequency of prevalent fungi isolated from stem cankers/lesions on declining hickory in three Midwestern States

		Number of Sites		Number of Trees	
State	Fungus species	Sampled	With fungus	Sampled	With fungus
Iowa	*Ceratocystis smalleyii*	3	--[1]	9	--
	Fusarium solani	3	2	9	2
Minnesota	*C. smalleyii*	2	2	8	5
	F. solani	2	2	8	6
Wisconsin	*C. smalleyii*	8	6	23	9
	F. solani	8	4	23	5

[1]Carrot disk isolation method failed to yield *Ceratocystis* spp.;
Small wood cube method replaced this method for Minnesota and Wisconsin samples.

cankers or lesions on stem. For pole-size hickories (5 to 12 inches d.b.h.), the observed tree crown and stem conditions included: 1) top dieback—small cankers on stem; 2) topkill—epicormic sprouts and sunken cankers on stem; 3) declining crown—callused, pock-marked stem; or 4) declining crown—*Phomopsis* galls on stem and branches. For sawtimber-size hickories (>12 inches d.b.h.), the tree crown and stem conditions observed included: 1) top dieback—epicormic sprouts; hickory bark beetle holes in main stem; or 2) declining crown—Phomopsis galls on stem and/or branches.

Fungi Associated with Sampled Stems

All of the *Ceratocystis* isolates (n = 19) were identified as *C. smalleyi* based on morphological and cultural characteristics. BLASTn searches for five isolates had nucleotide identities of 99 percent and E values of 0.0, which further supported our identifications. Examination of all isolates by T.C. Harrington confirmed the above identities. *Ceratocystis* spp. were not obtained from any of the stem samples collected in Iowa using the carrot disk method; however, *C. smalleyi* was commonly obtained using the wood cube method from bitternut hickory sampled in the Minnesota and Wisconsin sites (Table 2). These isolates were commonly from trees with evidence of hickory bark beetle activity; a few were obtained from discolored xylem behind beetle larval galleries.

All of the *Fusarium* isolates (n=15) were identified as *F. solani* (teleomorph = *Nectria haemtococca*) based on morphological and cultural characteristics. BLASTn searches for eight isolates had nucleotide identities of 99 percent and E values of 0.0 (Pennsylvania State University Fusarium Center sequence database at http://fusarium.cbio.psu.edu), which further supported our identifications. All isolates were obtained via wood chip plating on APDA or MYEA+SS. These isolates were associated with sunken, annual cankers associated with top dieback of bitternut trees; callused cankers on upper or lower main stems exhibiting small holes typical of pin-hole borers; or sunken cankers on bitternut with heavy crown dieback and epicormic branches.

Based on host association, the *Phomopsis* isolates (n=4) could only be identified as *Phomopsis* sp. However, *Diaporthe* species are commonly teleomorphs of *Phomopsis* species, and two *Diaporthe* (*D. apocrypta* and *D. hickoriae*) have been reported on hickories (Farr and others 1989). BLASTn searches in GenBank for DNA sequences of two isolates matched with two different *Phomopsis* species, *P. amygdale* (99 percent identity; E=0.0) and *Diaporthe helianthi* (anamorph = *Phomopsis* sp.) (99 percent identity; E=0.0). These were obtained from either elongate, rough-bark swellings on branches or main stems of saplings, or from discolored wood of top-killed, pole-size bitternut.

A variety of insect damage types was found on sampled trees. Entry/exit holes, egg niches, and larval galleries of the hickory bark beetle were the most common type of insect damage observed (two sites in Iowa; five sites in Wisconsin). Adult bark beetles were observed in holes or galleries on two sites. Round-headed wood borer larvae (Coleoptera: Cerambycidae) and/or galleries were observed on trees at two Wisconsin and one Minnesota sites. Flat-headed wood borer larvae (Coleptera: Buprestidae: *Agrilus* sp.) and/or galleries were observed on declining trees in one Minnesota and one Wisconsin site. Holes characteristic of pin-hole borers (Coleoptera: Scolytidae) were observed in trees in the Minnesota sites; the holes were commonly found in the center of sunken, annual cankers, but also occurred elsewhere. No adults were obtained from dissected stems. Lastly, mined cavities similar to those of phloem- and cambium-invading borers were associated with callused-over wounds on stems in three locations in Iowa and Minnesota. No adults were obtained from dissected stems.

DISCUSSION AND FURTHER STUDIES

In general, stand- to landscape-level decline and mortality of hickory have been attributed to drought periods and severe infestations of the hickory bark beetle. However, our preliminary survey found a more complex situation in 11 stands sampled in Iowa, Minnesota, and Wisconsin in 2006. Based on presence of stem cankers/galls and signs of observed bark- and wood-feeding insects, individual tree decline in affected stands appeared to be caused by more than just hickory bark beetles and drought. We hypothesize that the situation was better characterized as a decline disease with interaction of long-term predisposing, short-term inciting, and chronic contributing factors (Sinclair and Lyon 2005). A detailed survey of affected stands in Iowa, Minnesota, and Wisconsin was initiated in 2007 to partially test this hypothesis.

Isolates of *C. smalleyi* described by Johnson and others (2005) were obtained only from hickory bark beetle infested trees. The authors described the consistent association of *C. smalleyi* with this insect as "unique among fungal species in the *C. fimbriata* complex" (Johnson and others 2005). In our preliminary survey, *C. smalleyi* was isolated from discolored wood behind diffuse cankers occurring on hickory bark beetle colonized trees in > 50 percent of sampled sites in Minnesota and Wisconsin. However, the fungus was not always associated with the beetle-attacked bitternut hickory. Insect activity was observed on several trees in a Minnesota and a Wisconsin site, but the fungus was not isolated from sampled stem sections. Conversely, *C. smalleyi* was isolated from discolored sapwood behind diffuse cankers on at least two trees without signs of beetle activity in two other sites. No published reports exist on the ability of *C. smalleyi* to cause diffuse cankers on sapling to sawtimber- size bitternut hickory and contribute to tree decline and mortality. Johnson and others (2005) demonstrated the ability of *C. smalleyi* to cause xylem discoloration on potted, 2-yr-old bitternut hickory, shagbark hickory, and pecan seedlings. In late May 2007, we inoculated sapling- and pole-size bitternut hickory with isolates of *C. smalleyi* to further investigate the pathogenicity of the taxon.

Fusarium solani was commonly isolated from discolored sapwood associated with sunken, annual cankers on bitternut hickory. This fungus is known to cause annual cankers on other hardwood species, especially other genera in the Juglandaceae (Carlson and others 1985, Farr and others 1989). It has not been reported on *Carya* species. Sapling- and pole-size bitternut hickories were inoculated with *F. solani* isolates in May 2007 to evaluate their pathogenic potential on this species.

The hickory bark beetle is a suspected vector of *C. smalleyi*. The fungus is commonly associated with beetle-colonized hickory; it has been commonly isolated from beetle galleries (Johnson and others 2005) and isolated from beetle adults by G. Smalley (per Johnson and others 2005). If *F. solani* is found to cause annual cankers of hickory, the role of ambrosia beetles in disseminating that fungus should also be investigated. Insect exit/entry holes and tunnel pattern characteristic of pin-hole borers were associated with sunken, annual cankers in our preliminary survey. Ambrosia beetles (*Xyleborus sayi* and *Xylosandrus germanus*) were consistently associated with *F. solani*-caused cankers on 6-yr-old yellow-poplar in a plantation, but their role as vectors was not confirmed (Anderson and Hoffard 1978). Future studies will determine the *C. smalleyi* (and *F. solani*, if appropriate) contamination frequencies for hickory bark beetles and ambrosia beetles emerging from bitternut hickory stems exhibiting diffuse or sunken, annual cankers.

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MANAGING JAPANESE STILTGRASS DOMINATED COMMUNITIES IN THE RIDGE AND VALLEY PHYSIOGRAPHIC PROVINCE IN EASTERN WEST VIRGINIA

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Abstract.—Japanese stiltgrass (*Microstegium vimineum*) is an exotic invasive species that can dominate forest understories and suppress native herbaceous and woody species. This study had two objectives: 1) to assess directed spray herbicides for controlling *M. vimineum*; and 2) to collect a set of factors that affect management of *M. vimineum* on the diverse properties of the Connors Hollow, WV, watershed. At 3 weeks following glyphosate and sethoxydim treatments, only glyphosate treatments showed significant differences in cover and mean percent change in height growth over the controls and other herbicide treatments. No significant differences in species richness were detected among herbicide treatments, although the three of four glyphosate treatments ranked lowest in richness. In discussions related to controlling *M. vimineum*, landowners helped to identify 12 major factors and 44 subcategories and issues affecting management of the invasive grass. End-of-season measurements and continued discussion of causal factors are slated for early in the fall of 2007.

INTRODUCTION

Japanese stiltgrass (JSG) (*Microstegium vimineum*) is an exotic invasive graminoid (Poaceae; Barden 1987) that is typically on lists of major plant pests in the eastern United States (e.g., WVDNR 2007). In West Virginia, this species is particularly problematic for landowners who value understory plants for commercial purposes. Native herbs like ginseng (*Panax quinquefolius*), goldenseal (*Hydrastis canadensis*), and black cohosh (*Cimicifuga racemosa*) are some of the common commercial medicinal plants that can be outcompeted and overgrown by *M. vimineum*.

M. vimineum is also a problem in areas where active landowners are interested in developing better wildlife habitat. In some areas, *M. vimineum* dominates the herb layer of vast tracts of forest and spreads rapidly as forest canopies are disturbed (Oswalt and others 2007). This grass is reportedly not used by wildlife (Miller 2003) which compounds the challenge for controlling *M. vimineum*, as wildlife species, notably white-tailed deer (*Odocoileus virginianus*), add additional biotic pressure to the other more palatable native and exotic flora (Waller and Alverson 1997). This preference leaves *M. vimineum* in an even more competitive position.

While broad spectrum herbicides (e.g., glyphosate-based products) are known to kill *M. vimineum*, these will also eliminate many of the associated (non-target) species that grow in close proximity. Pomp and others (in press) found that *M. vimineum*-dominated plots that were treated with both single and double applications of graminicide showed average species richness values that were significantly higher than glyphosate, weed whip, and untreated plots.

Other studies have explored various treatments for controlling stiltgrass using graminicides (Judge and others 2005a, 2005b). These treatments aim to reduce incidental damage to associated species, although herbicide impact to associated herbaceous species have generally not been included in treatment

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assessments. Associated species are important as they are potential replacements for *M. vimineum* in ecosystem restoration projects (D'Antonio and Meyerson 2002).

This paper reports first-year results of an *M. vimineum* project to 1) assess various directed herbicide spray rates and chemicals; and 2) begin to clarify other factors that might be related to the successful control of *M. vimineum* in the Connors Hollow watershed.

STUDY AREA

Connors Hollow watershed is a 14-digit watershed located in Morgan County in the eastern panhandle of West Virginia. The forest is dominated by chestnut oak (*Quercus prinus*), white oak (*Q. alba*), and black oak (*Q. velutina*) on the ridges and by many of these same species with yellow-poplar (*Liriodendron tulipifera*), black walnut (*Juglans nigra*), and maples (*Acer* spp.) on the lower reaches of the watershed. In many areas, the canopy has been broken by past timber harvests. In some places, tree-of-heaven (*Ailanthus altissima*) has become established and dominates the overstory.

Understory is sparse with clear browse lines from white-tailed deer. In some areas there is little green on the forest floor; in others, there is a heavy, nearly complete herbaceous layer of *M. vimineum*. Shrub species are predominately black huckleberry (*Vaccinium* spp.), spicebush (*Lindera benzoin*), and Japanese barberry (*Berberis thunbergii*).

RESEARCH METHODS

Directed Spray Treatments

We used a point-intercept system to monitor this herbicide screening. Aluminum angle stakes were set up 22 ft apart in areas with 100 percent *M. vimineum* cover. Measurements were made by stretching a metal logger's tape from stake to stake and placing a PVC pole 0.75 inches in diameter in a vertical position every 2 ft beginning at the 2-ft mark on the tape. The height of the tallest JSG plant touching the pole was recorded to the nearest 2 inches.

Pretreatment measurements were conducted in early June 2007 and just prior to treatment on July 14, 2007. One 3-week post treatment (3WAT) measurement was conducted on August 3, 2007 along with an herbaceous species survey using a systematic meander where two observers moved up one side of the plot and down the other recording all herbaceous and woody species. During this census, all herbaceous and woody species less than 4.5 ft were recorded. An end-of-growing season measurement of *M. vimineum* was recorded 10WAT on September 16, 2007.

Herbicide treatments were limited to glyphosate and sethoxydim. These were selected to represent a broad spectrum herbicide (glyphosate; applied as Accord®) and a graminicide (sethoxydim; applied as Poast®). Target spray areas were flagged to surround the 22-ft measurement plot in an approximate 25-ft by 30-ft area. These were laid out to provide a visual target area surrounding the measurement plot. One pass was made over this entire area. If residual herbicide was in the tank, the sprayer would go outside of this area to empty the tank before washing and mixing a new treatment. Two tanks were used for the treatments. One tank was reserved for the glyphosate treatments and the other for the sethoxydim treatments.

The treatments were applied using solo backpack sprayers and a fan nozzle. The herbicide was sprayed in a systematic fashion in a manner that might be used by landowners desiring to treat *M. vimineum* on their own properties. Plots were sprayed along the edges first, then down the central measurement area, and finally outside of the flagged area to eliminate the residual herbicide in the tank. Approximately one quart of mixture was used for each treatment area. This treatment approach does not let us estimate the application rate per treatment area. However, it does provide the opportunity to give landowners an idea of how they might treat other areas as they commonly mix and apply herbicides on a percentage basis.

Two rates of each herbicide were used with and without a recommended surfactant. Surfactants included Entry II® (an ethoxylated fatty amine) with the glyphosate treatments and crop oil concentrate with the sethoxydim treatments. Both herbicides were applied using a 1.5 percent and 0.25 percent volume to volume (herbicide:water) rate. A control and a control with surfactant (Entry II) plots were also included in the study. Three replicates of each herbicide treatment were established.

Percent cover and percent post-treatment change in height were used a dependent variables in a completely randomized analysis of variance (PROC GLM, SAS 9.1 software; SAS Institute, Cary, NC, 2003).

RESULTS

Measurements taken at both 3WAT and 10WAT showed that glyphosate had the most visible effectiveness. These treatments had essentially desiccated all *M. vimineum* on the plots and at 3WAGT had the only plots that deviated from the initial 100 percent *M. vimineum* cover. Low glyphosate (0.25 percent V:V) averaged 52 percent cover and high glyphosate (1.5 percent V:V) averaged 3 percent cover of *M. vimineum*. All other plots retained their 100 percent cover of *M. vimineum*.

Measurements taken 10 WAT demonstrated significant differences in mean *M. vimineum* percentage cover and relative post-treatment growth rates. All herbicide treatments had statistically different height growth rates compared with control plots (Fig. 1, Table 1). In general, glyphosate treatments were statistically different from both control and sethoxydim treatments with *M. vimineum* in high (1.5 percent) glyphosate plots all but disappeared from the plots with a decrease in height of 98 to 100 percent and 0 to 7 percent cover (Table 2).

Three weeks post treatment, 148 different species of woody and non-woody plants were found on the treatment plots (Table 3). Although the three glyphosate treatments had the lowest species richness of all other plots (Table 3), these differences were not statistically different (p=0.72) and the low glyphosate treatment with a surfactant added had the highest species richness values.

Table 1.—Average percentage change in height between pretreatment measurements to 10 weeks after treatment. Percentages followed by different letters are statistically different (Duncan's mean separation procedure; alpha=0.05).

Treatment	Change in height (%)
Control, no surfactant	20 a
Control, surfactant	16 a
0.25% sethoxydim, surfactant	-20 b
0.25% sethoxydim, no surfactant	-31 bc
1.5% sethoxydim, no surfactant	-60 cd
0.25% glyphosate, surfactant	-61 cd
1.5% sethoxydim, surfactant	-63 cde
0.25% glyphosate, no surfactant	-92 def
1.5% glyphosate, no surfactant	-98 ef
1.5% glyphosate, surfactant	-100 f

Table 2.—Percent cover of *M. vimineum* 10 weeks following herbicide treatments. Percentages followed by different letters are statistically different (Duncan's mean separation procedure; alpha=0.05).

Treatment	Percent cover
Control, no surfactant	100 a
Control, surfactant	100 a
0.25% sethoxydim, no surfactant	100 a
0.25% sethoxydim, surfactant	100 a
1.5% sethoxydim, surfactant	80 ab
1.5% sethoxydim, no surfactant	77 ab
0.25% glyphosate, surfactant	53 ab
0.25% glyphosate, no surfactant	37 bc
1.5% glyphosate, no surfactant	7 c
1.5% glyphosate, surfactant	0 c

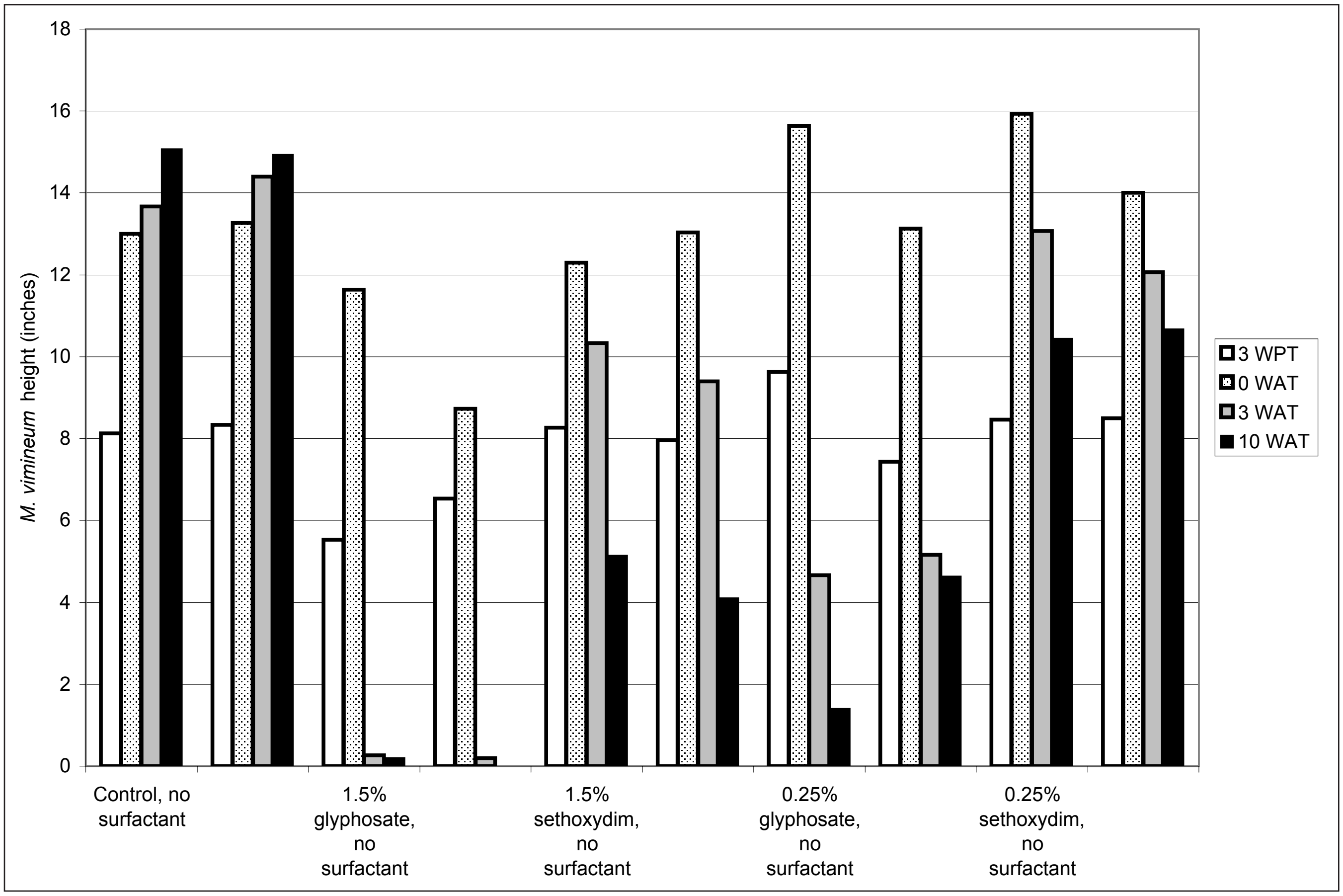

Figure 1.—Average heights of *M. vimineum* 3 weeks prior to treatment (3 WPT), immediately prior to treatment (0 WAT), 3 weeks after treatment (3 WAT), and 10 weeks after treatment (10 WAT). Note: Table 1 shows statistical comparison among treatments for the percentage change in height between 0 WAT and 10 WAT.

During the summer of 2007, as the herbicide portion of this project was being implemented, we compiled a list of factors, opinions, and ideas related to the *M. vimineum* problem in the watershed. These were recorded from informal sessions among the authors and collaborators of this paper and with members of the Seldom Seen Hunt Club of Connors Hollow. These informal sessions took place on June 7, July 14, and August 3, 2007. Notes from sessions were gleaned for major factors by the lead author and sent to collaborators for comments and additions. This list is intended to be a first step in developing a causal loop diagram (Maani and Cavana 2000) to help identify interrelationships among variables associated with M. vimineum. Table 3 lists a preliminary set of key variables and ideas related to managing *M. vimineum* and serves as the first step in this causal loop modeling process. In all, there were about 12 categories with 44 subcategories of issues that were related to factors possibly affecting the persistence and management of *M. vimineum* (Table 4).

DISCUSSION

The results of the herbicide trial were somewhat surprising, especially the seeming lack of control in the sethoxydim treatments. However, Judge and others (2005a) showed that sethoxydim in outdoor container experiments had 78 percent control at 4 weeks after treatment, which increased to 99 percent control 8 weeks following treatment. Our findings may be the result of late applications or variability due to local climate, although plants appeared to be healthy and not drought-stressed at the time of treatments. Indeed, the *M. vimineum* plants showed signs of stunting and the measurements indicate a decrease in plant size.

Table 3.—Twenty most common tree species and 20 most common semi-woody and herbaceous species found 3 weeks post-treatment on 30 *M. vimineum* study plots. Total number of species < 4.5 ft was 148.

Scientific name	Common name	Number of plots
	-----------Tree species-----------	
Ailanthus altissima	Tree-of-heaven	15
Fraxinus americana	White ash	13
Liriodendron tulipifera	Yellow-poplar	12
Carya glabra	Pignut hickory	11
Acer rubrum	Red maple	10
Acer saccharum	Sugar maple	7
Quercus alba	White oak	6
Quercus rubra	Red oak	6
Robinia pseudoacacia	Black locust	5
Ulmus americana	American elm	3
Amelanchier	Serviceberry	2
Pinus strobus	Eastern white pine	2
Betula lenta	Sweet birch	1
Carpinus caroliniana	American hornbeam	1
Nyssa sylvatica	Black gum	1
Ostrya virginiana	Hop hornbeam	1
Pinus virginiana	Virginia pine	1
Quercus prinus	Chestnut oak	1
Sassafras albidum	Sassafras	1
Juglans nigra	Black walnut	1
	-----------Other woody and herbaceous species-----------	
Viola sororia	Common blue violet	21
Amphicarpa bracteata	Hog-peanut	16
Polygonum persicaria	Spotted ladysthumb	15
Alliaria petiolata	garlic mustard	14
Oxalis stricta	Common yellow oxalis	11
Perilla frutescens	Beefsteak plant	11
Panicum clandestinum	Deertongue	9
Parthenocissus quinquefolia	Virginia creeper	9
Potentilla simplex Michx.	Common cinquefoil	9
Smilax rotundifolia	Roundleaf greenbrier	9
Cynoglossum virginianum	Wild comfrey	8
Dichanthelium boscii	Bosc's panicgrass	8
Leersia virginica	Whitegrass	7
Lycopus virginicus	Bugleweed	7
Rubus spp.	Blackberry	7
Vitis vulpina	Frost grape	7
Galium concinnum	Shining bedstraw	6
Galium circaezans	Licorice bedstraw	6
Galium triflorum	Sweet-scented bed straw	6
Muhlenbergia schreberi	Nimblewill	6

Table 4.—Main categories of factors and issues related to management of *M. vimineum* in Connors Hollow watershed. These were elicited from Connor's Hollow watershed stakeholders.

Main category	Subcategory/Issues
Japanese stiltgrass	• Will herbicide affect seed viability?
	• What is the best way to control JSG?
	• Stiltgrass will always be here.
	• Weedwhip treatments in sensitive areas.
	• Herbicide treatments applied 07/14/07.
	• Do we kill stiltgrass first or tree-of-heaven?
Gypsy moth	• Linked to stiltgrass?
	• Applying for spring 2008 spraying.
Awareness	• Most people aren't aware of the JSG problem.
	• JSG is only present from June to September.
Timbering	• Timbering in the late 1980s, no JSG, some TOH.
	• Timber harvested about 5 years ago, JSG came in.
Hemlock woolly adelgid	• Can hemlock recover?
	• Can JSG move into area affected by the HWA?
Wildlife	• How does JSG affect wildlife?
	• At least some cover of JSG. Good?
	• What is the habitat quality of JSG?
	• Bears can be a problem with tree tubes.
Aesthetics	• JSG looks very attractive.
	• Most people would probably like the appearance.
Herbicide control	• Not good to spray herbicides everywhere.
Conservation easements	• Several landowners developing easements.
Deer	• Are there too many? Too few?
	• Chronic wasting disease is nearby.
	• Deer browse line is present.
	• What are deer eating? Understory is barren.
	• Deer are eating TOH sprouts.
Tree-of-Heaven	• Seldom Seen Hunt Club treating TOH.
	• Garlon 3E hack-and-squirt yields good results.
Other invasive species	• In absence of stiltgrass, what will come in next?
	• Other species benefit if stiltgrass is killed?
Different landowners	• Perrier Water Company, Hunt Clubs, Cacapon State Park, Private Individuals, Length of ownership, History of associations with Connors Hollow.
Organizations	• WV Division of Forestry, Westvaco/NewPage Corporations, WVU Extension Service, Cacapon Institute, Potomac Conservancy, WV Division of Agriculture (gypsy moth).

On high sethoxydim plots, *M. vimineum* individuals had damaged terminal shoots (location of flowers). A key question remains: Can the stunting by this graminicide prevent flowering or seed set?

Species richness was high on these plots, with 144 different species identified. Unlike Pomp and others (In press), no clear statistical differences in species richness were established. The general rankings, however, with three of four glyphosate treatments having the fewest species on those plots, suggest more research is needed to find an herbicide that will kill stiltgrass and leave other plants intact when used in restoration projects.

Factors elicited from landowners and members of a local hunting club are an important starting point in integrating herbicide prescriptions with the other factors related to management. For example, deer browsing is a significant biotic pressure that can impede even the most successful *M. vimineum* treatment. Lack of *M. vimineum* might increase browsing of plants hidden by the grass. This interrelationship is only one of many we hope to continue to investigate in our effort to control exotic species in Connors Hollow watershed.

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THE EXTENT OF SELECTED NON-NATIVE INVASIVE PLANTS ON MISSOURI FORESTLAND

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Abstract.—The Northern Research Station's Forest Inventory and Analysis Program (NRS-FIA) collects forest-related data throughout a 24-state region in the northeastern United States, ranging from North Dakota to Maine and Kansas to Maryland. Based on discussions with stakeholders and others, NRS-FIA found that the impact of non-native invasive plants (NNIPs) may be known at the local level but their regional abundance, impact, range, and rate of spread are not well understood. In 2005 and 2006, NRS-FIA sampled for the presence and percent cover class of 25 selected non-native invasive species on forested plots in the Upper Midwest states. The species were selected based on the threat posed to our forested ecosystems, the extent of their range, detectability of these species in summer or winter, and level of interest by our stakeholders.

This paper summarizes findings from 2 years of sampling in the State of Missouri. Data are summarized by forest type and the relationship between forest cover and the impact of human influences (represented by variations in overstory basal area and distance to roads) is examined. Fifty-eight percent of the plots sampled had no invasive species of interest on them. Of the 25 species sampled for in the 2005 and 2006 inventory panels, only 13 were found in Missouri and only three—multiflora rose, non-native bush honeysuckles, and Japanese honeysuckle—were found in any number. There was no apparent relationship between forest type and NNIP presence. We examined physiographic class code to determine any influence of topography (and—by extension—water availability/site productivity) upon NNIP presence. Site quality (higher site index for multiflora rose) and topography (level sites for multiflora rose and Japanese honeysuckle) were significantly related to invasive species presence. We found a significant relationship with mesic or hydric sites for multiflora rose and Japanese honeysuckle, although relatively few of our target species were found in hydric systems (a function of our species list and the emphasis on forested lands in Missouri). Finally, examination of distance to road, a surrogate for road density, found a significant negative relationship with multiflora rose and Japanese honeysuckle presence. Caution must be taken in interpreting these results. Since much of the landscape had been harvested and/or otherwise disturbed, the current road system might not reflect past patterns of habitation and transport.

INTRODUCTION

Non-native invasive plants (NNIPs)[2] are expanding their distributions across North America. NNIP occur in all the major plant-life forms found in forest ecosystems: trees, shrubs, vines, herbs/forbs, and grasses. Generally, vectors that contribute to the spread of non-native invasive plants, e.g., highways, contribute to the spread of more than one species or life form. Introduction, however, does not necessarily mean establishment. A specific sequence of timing and site must occur for an exotic to take hold in an ecosystem. Once established, NNIP threaten the sustainability of native forest composition, structure, function, and resource productivity (Webster and others 2006). Richardson and Pyšek (2006) outlined four factors of invasibility:

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[2]This paper will also refer to NNIPs as "exotics" or "invasives."

disturbance, competitive release, resource availability, and competitive pressure. This paper examines some of these factors by documenting the relationship between exotic presence and forest type, overstory basal area, disturbance (road density), and site factors (site index, aspect, and physiographic class code).

STUDY OBJECTIVES

This study has three objectives: document the distribution of species, compare invasive presence to site characteristics, and examine the role of disturbance in invasive species presence and coverage. The full extent of NNIPs has not been documented statewide on FIA plots in Missouri. A principal benefit of NRS-FIA's efforts was to provide an estimate of extent and location of exotics on the forested landscape of the State. Non-native invasive plants, like all plants, respond to supplies of water, nutrients, and light. Where these exotics excel is in their ability to capture and utilize these resources more quickly and more completely than their native competitors. This analysis searched for patterns of resource utilization and competitive advantage for the exotics. For the purpose of this paper, site characteristics included those variables pertaining to aspect and physiographic class code (topographic position). Human influence is responsible for both long-distance and local transport of the exotic species and often for creating the landscape that facilitates establishment and spread of the invasive. We examined both of these roles by evaluating the influence of distance to roads and the residual effects of a forest's disturbance history: overstory basal area and overstory diversity.

BACKGROUND

Located at the intersection of several ecoregions, Missouri had many different presettlement forest compositions and structures, ranging from high upland forest in the Ozarks to bottomland ecosystems in the "Bootheel" to savannas and prairies in the northern and western parts of the State. The fertile soils of this region were ideal for farming, and settlers proceeded to clear the land for agriculture. In the heavily timbered areas of southern Missouri, large-scale commercial harvesting exploited the magnificent stands of shortleaf pine and other species, while subsequent fires and lack of scientific management resulted in a radically altered forested landscape (Beilmann and Brenner 1951). The combination of clearing, settlement, and timber harvesting created a highly fragmented landscape, offering many opportunities for non-native invasive plants to become established in forests.

METHODOLOGY

Meaningful exotic-invasive plant inventory requires a large network of sample plots measured consistently over time. Over the past decade, the USDA Forest Service, Forest Inventory and Analysis (FIA) program has implemented an inventory system that seeks to achieve national and international consistency[3]. This system utilizes three phases of inventory designed to make estimates of forest extent, composition, structure, health, and sustainability: phase 1—remote sensing, phase 2—systematic grid of ground samples, and phase 3—subset of more detailed forest health ground-based samples (McRoberts 1999). For FIA purposes, the state of Missouri is divided into five inventory units. Based broadly on ecological characteristics, they are Eastern Ozarks, Southwest Ozarks, Northwest Ozarks, Prairie (in the north and western portion of the state), and Riverborder (along the lower Missouri and Mississippi Rivers).

[3]Complete documentation of the plot design and all measurements is at http://socrates.lv-hrc.nevada.edu/fia/dab/databandindex.html.

Table 1.—Non-native invasive plants surveyed on FIA plots in the Upper Midwest of the U.S., 2005-2006

COMMON NAME	SCIENTIFIC NAME	COMMON NAME	SCIENTIFIC NAME
Woody species		**Grasses**	
Multiflora rose	*Rosa multiflora*	Reed canary grass	*Phalaris arundiacea*
Japanese barberry	*Berberis thunbergii*	Phragmites, Common reed	*Phragmites australis*
Common buckthorn	*Rhamnus cathartica*	Nepalese browntop, Japanese stiltgrass	*Microstegium vimineum*
Glossy buckthorn	*Frangula alnus*	**Herbaceous**	
Autumn olive	*Elaeagnus umbellata*	Garlic mustard	*Alliaria petiolata*
Non-native bush honeysuckles	*Lonicera* spp.	Leafy spurge	*Euphorbia esula*
European privet	*Ligustrum vulgare*	Spotted knapweed	*Centaurea bierbersteinii*
Vines		Dame's rocket	*Hesperis matronalis*
Kudzu	*Pueraria montana*	Mile-a-minute weed, Asiatic tearthumb	*Polygonum perfoliatum*
Porcelain berry	*Ampelopsis brevipendunculata*	Common burdock	*Arctium minus*
Asian bittersweet	*Celastrus orbiculatus*	Japanese knotweed	*Polygonum cuspidatum*
Japanese honeysuckle	*Lonicera japonica*	Marsh thistle	*Cirsium palustre*
Chinese yam	*Dioscorea oppositifolia*		
Black swallowwort	*Cynanchum louiseae*		
Wintercreeper	*Euonymus fortunei*		

NNIP Sampling Scheme

During 2005-2006, 100 percent of all Phase 2 forested plots were assessed for presence and cover of any of 25 non-native invasive woody, vine, grass, and herbaceous species of interest[4] (Table 1). If a species on the list was found, the percent cover was estimated and placed into one of seven codes, ranging from 1 (trace) to 7 (76 to 100 percent) (Table 2).

Table 2.—Cover codes and ranges of percent cover of non-native invasive plants used in recording invasive species' presence, FIA plots, 2005-2006

Cover code	Range of percent cover
1	< 1 percent, trace
2	1 to 5 percent
3	6 to 10 percent
4	11 to 25 percent
5	26 to 50 percent
6	51 to 75 percent
7	76 to 100 percent

Spatial analyses were conducted using geographic information systems (GIS). Distances to roads were computed as the minimum Euclidean distance (m) from each plot center to the nearest road transect included within the Environmental Systems Research Institute, Inc. (ESRI, Redlands, CA) Street maps dataset (version 2005 with 2006 updates). Road density was determined by overlaying plot locations on the "Forest Intactness of the Coterminous United States, April 2001" dataset, distributed by the Conservation Biology Institute (Corvallis, OR). Road densities and other landscape metrics within this dataset, were estimated within forestland units defined by highways and urban areas that contained more than 50,000 people.

Distances from FIA plots (true plot location coordinates) to roads were calculated with a GIS, for each of five categories of roads within the ESRI Street Maps dataset. Distances were calculated simultaneously from all plots across the seven states to National Freeway, State Freeway, and Major Highway features. Processing

[4]This list was not exhaustive but represented those species likely to have a significant impact somewhere in the 11-state Upper Midwest.

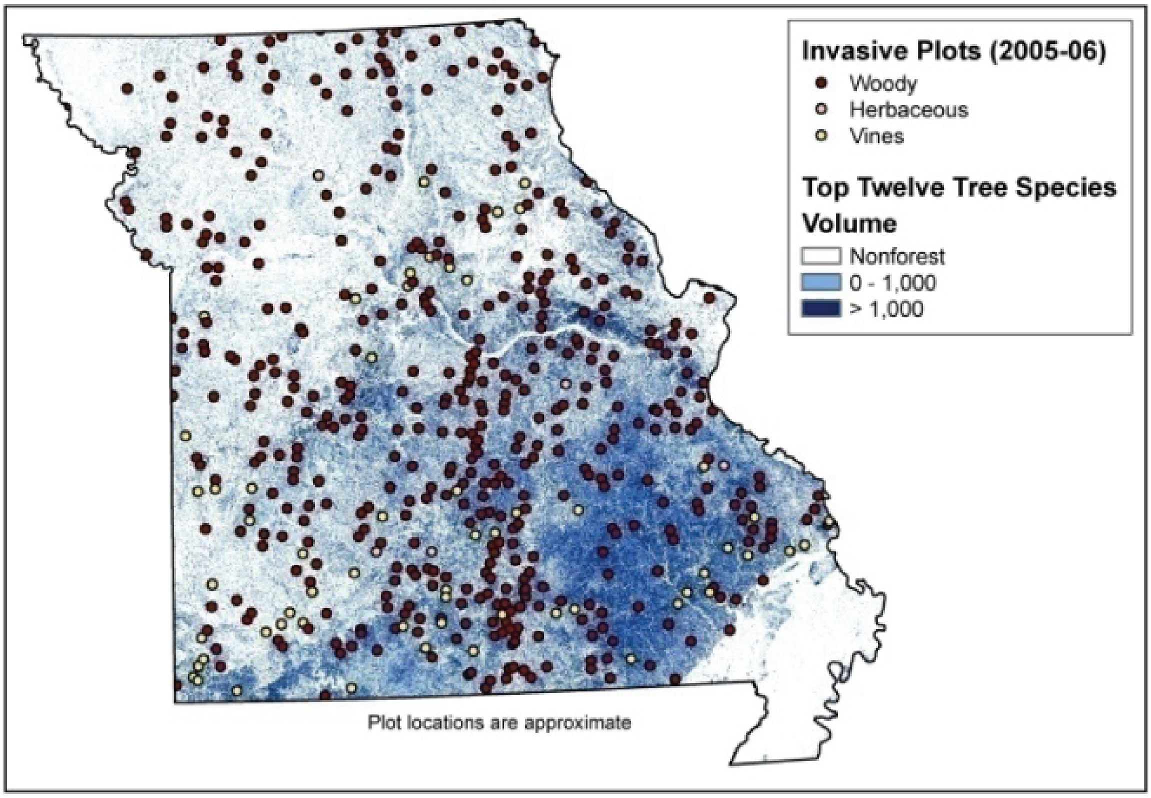

Figure 1.—Distribution of plots with non-native invasive plants in Missouri, 2005-2006. The blue shades in the background represent the volume (in ft^3 ac^{-1}) of the top 12 tree species in the Upper Midwest.

the relationship between plots and the large number of local roads within Minor Highway and Local Street features was constrained to search for the nearest Minor Highway and Local Street within a 6 to 15 mile buffer radius of each plot. Buffer radius varied by state, including a 12-mile buffer around each state to allow for more representative calculations from plots near state boundaries.

During analysis, if a plot was missing a value for a specific combination of variables, we dropped the plot from the analysis for the variable.

RESULTS

Invasive Plants in Missouri Forests

Of the 25 species sampled for in the 2005 and 2006 inventory panels, only 13 were found in Missouri and only three—multiflora rose (457 plots), non-native bush honeysuckles (89), and Japanese honeysuckle (69)—were found in any number. Of the 1,264 plots sampled in this study 734, or 58 percent, had no invasive species of interest on them. Multiflora rose was the most frequently found species, present on 36 percent of the plots.

Figure 1 displays the distribution of invasives across Missouri's forests. The underlying forest volume map, for this and subsequent figures, was derived from a nearest neighbor imputation of FIA plots to a phenological series of satellite imagery from the Moderate-Resolution Imaging Spectroradiometer. The prominence of woody invasive species is particularly evident. Note the relative lack of herbaceous exotics on NRS-FIA plots.

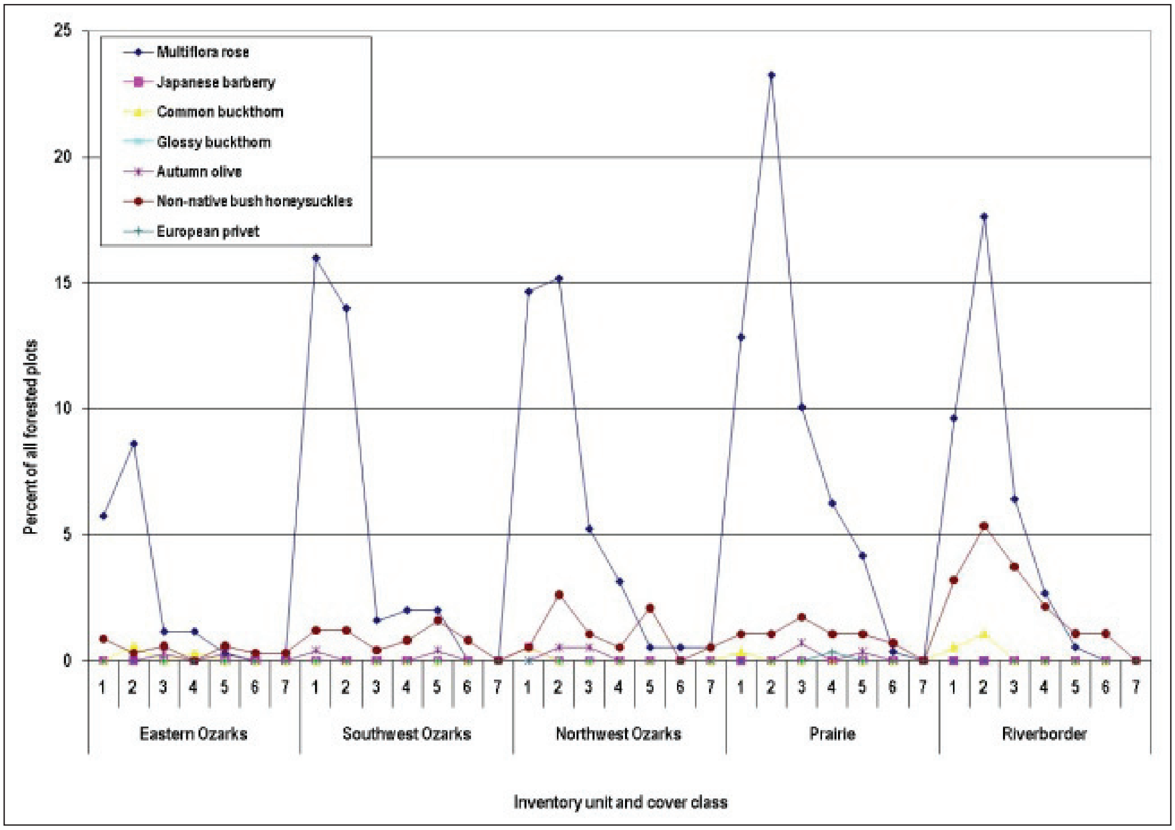

Figure 2.—Percentage of forested plots with non-native invasive woody plants in Missouri, 2005-2006. The numbers in the bottom axis represent cover codes from 1 (trace) to 7 (76-100 percent). Cover class "0"—no invasives found—not shown in order to preserve graphic scale.

Multiflora rose was found on more plots than any other invasive species, and was particularly prevalent in the Prairie and Riverborder inventory units (Fig. 2). These two units represent areas with some of the historically highest levels of Euro-American settlement and disturbance.

Herbaceous NNIPs were not particularly prevalent on NRS-FIA sample plots in Missouri (Fig. 3), although there were some local concentrations. Common burdock was the most frequently found species.

Among the vines, Japanese honeysuckle was the most numerous and had a large number of plots in the higher percent cover classes (Fig. 4).

Earlier, we documented the total number of plots with particular alien plant species. But when we looked only at the exotic species with the greatest percent cover on the plot, multiflora rose was again the most prevalent species on 381 plots or 30 percent of all plots sampled in 2005-2006, followed by non-native bush honeysuckles (74 plots/6 percent) and Japanese honeysuckle (56 plots / 4 percent) (Table 3; Figures 5-7).

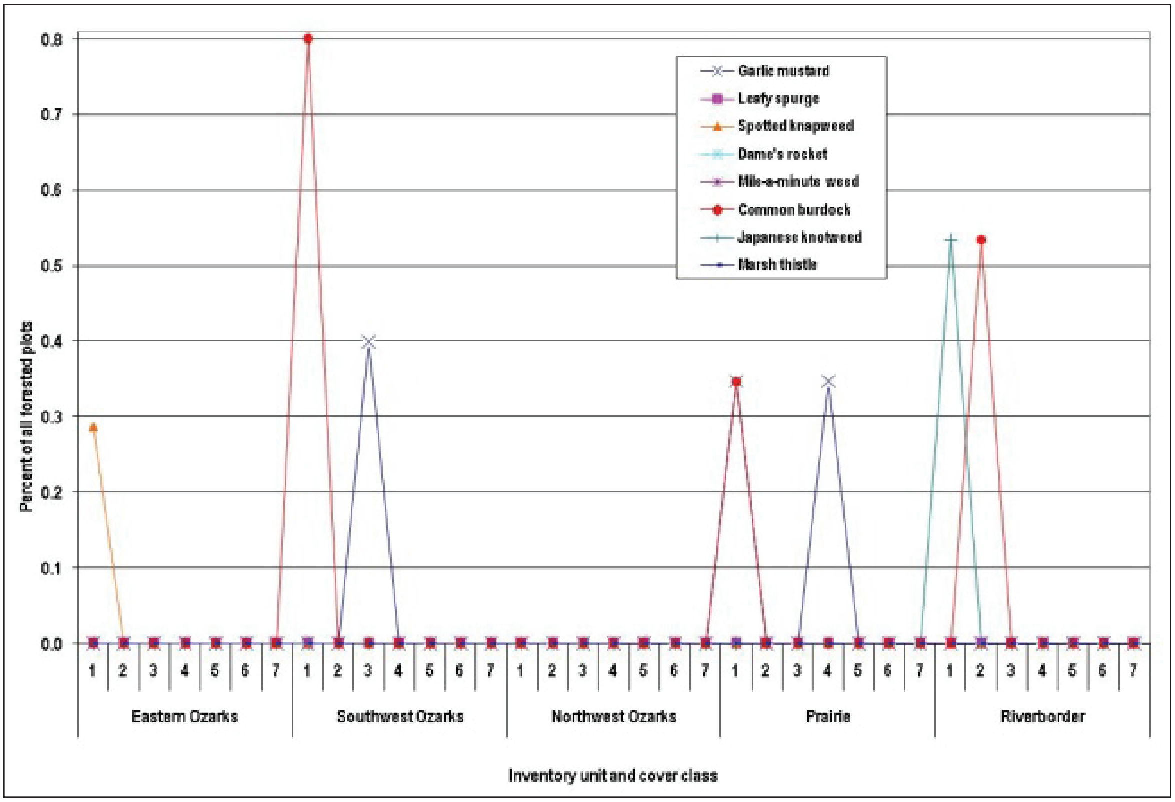

Figure 3.—Percentage of forested plots with non-native invasive herbaceous plants in Missouri, 2005-2006. The numbers in the bottom axis represent cover codes from 1 (trace) to 7 (76-100 percent). Cover class "0"—no invasives found—not shown in order to preserve graphic scale.

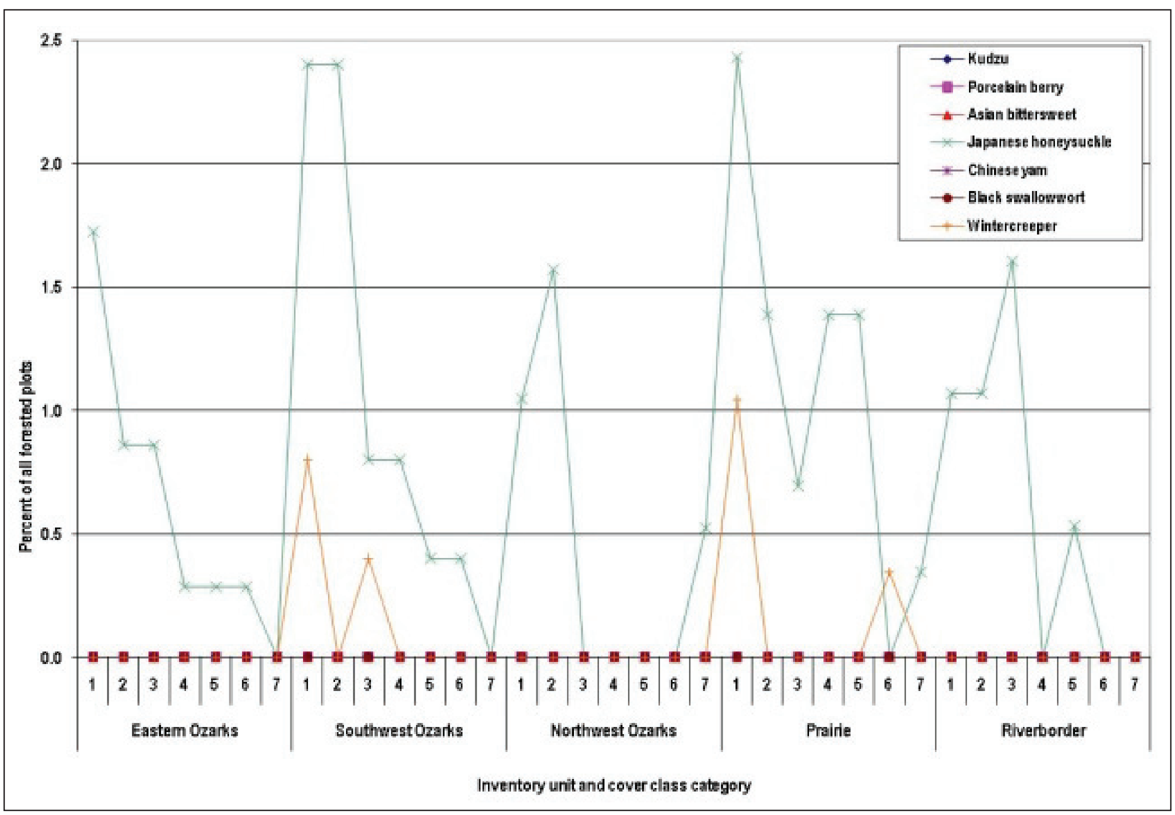

Figure 4.—Percentage of forested plots with non-native invasive vines in Missouri, 2005-2006. The numbers in the bottom axis represent cover codes from 1 (trace) to 7 (76-100 percent). Cover class "0"—no invasives found—not shown in order to preserve graphic scale.

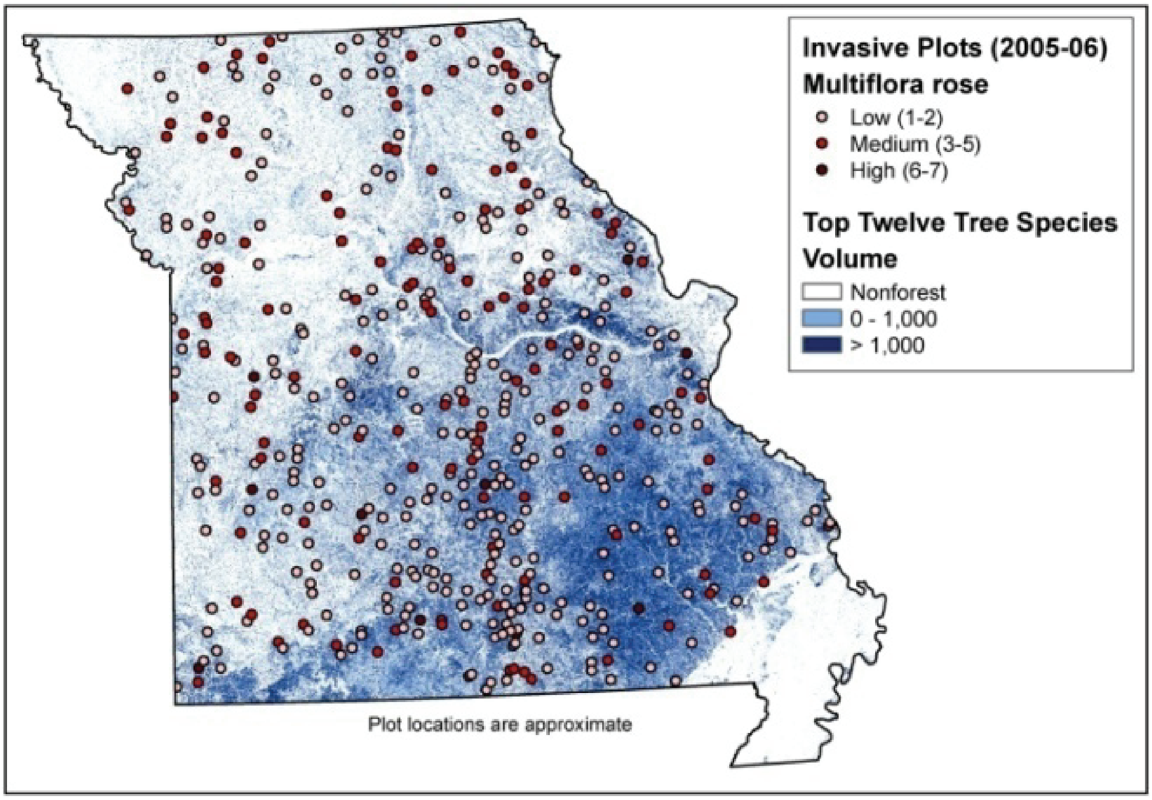

Figure 5.—Distribution of plots with multiflora rose present, by cover class, Missouri 2005-2006. The blue shades in the background represent the volume (in ft^3 ac^{-1}) of the top 12 tree species in the Upper Midwest.

Prominent Invasive Plants

Multiflora Rose

Multiflora rose (*Rosa multiflora*) is a widespread shrub introduced as rootstock for ornamental roses in 1866 (Plant Conservation Alliance 2006). The species was distributed and planted widely for erosion control, "living fences" for livestock, and cover for wildlife. Multiflora rose spreads quickly and establishes dense cover that shades out other plants. Its seeds are dispersed by birds and remain viable in the soil for many years. It is currently found across the U.S. and is classified as "noxious" in several states. Control methods include mechanical and chemical methods that require repeated application for success, making control very expensive (Evans 1983).

Non-native Bush Honeysuckles

Non-native bush honeysuckles are natives of eastern Asia and were brought to the U.S. to use as ornamentals and for wildlife habitat. Two of the most common NNIPs of the genus in Missouri are Morrow's honeysuckle (*Lonicera morrowii*) and Amur honeysuckle (L. *maackii*). Fragmented forest remnants are vulnerable to honeysuckle invasion and establishment, particularly sites with limestone geology, which is prominent in Missouri. They frequently become well established on the forest edge (Luken and Goessling 1995). They not only outcompete native shrubs, but also reduce understory diversity by shading forest floor wildflowers. These *Lonicera* species produce small juicy berries that are eaten by many species of small mammals and birds. Honeysuckles are generally believed to have a minimal interval between dispersal and germination and a short-lived seed bank. The species relies on the heavy seed output and sprouting from buds at the base of the stems on large plants to increase its population size (Luken 1988).

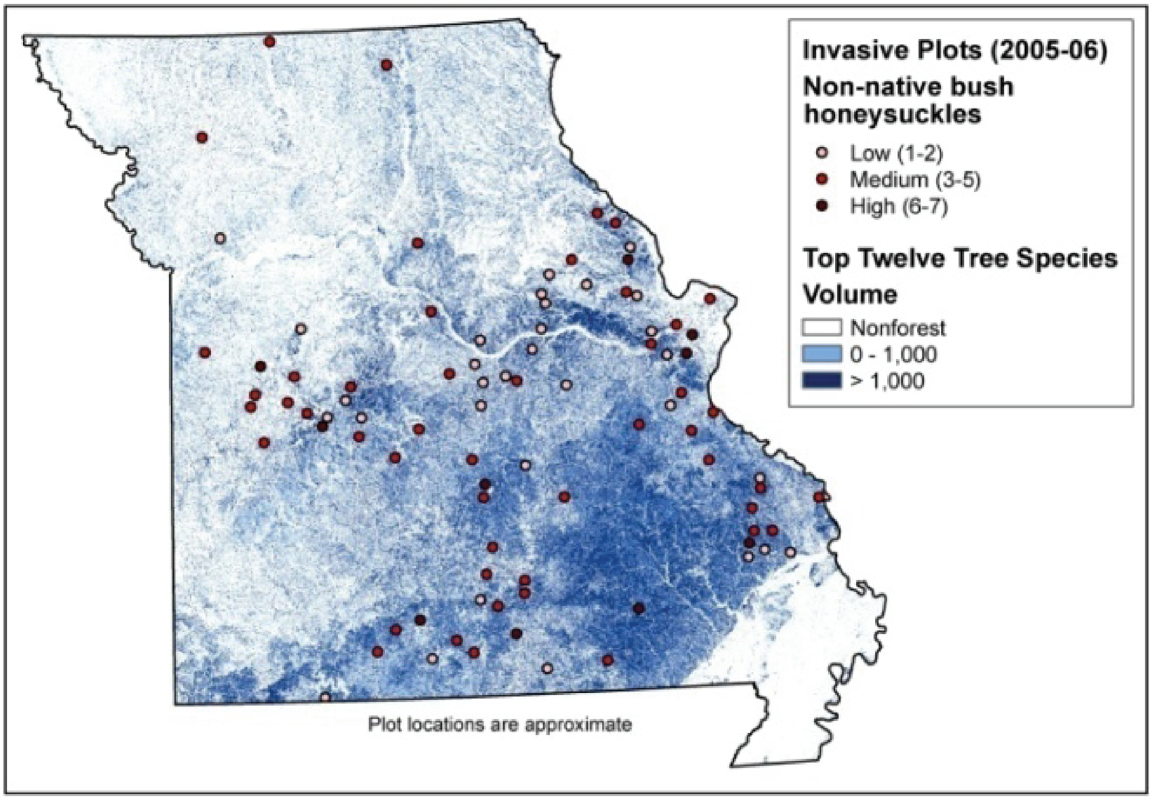

Figure 6.—Distribution of plots with non-native bush honeysuckle species present, by cover class, Missouri 2005-2006. The blue shades in the background represent the volume (in $ft^3 ac^{-1}$) of the top 12 tree species in the Upper Midwest.

Japanese Honeysuckle

Japanese honeysuckle (*Lonicera japonica*) is a persistent vine introduced as an ornamental and for erosion control and wildlife habitat in the mid-1800s (Plant Conservation Alliance 2006). The species thrives in a wide variety of habitats and quickly becomes established on disturbed sites (Rhoads and Block 2000). It can withstand shade and survive on marginal habitats until conditions improve (Ohio Department of Natural Resources 2001). It is currently distributed in most states including Hawaii, but is limited by cold temperatures and low precipitation (Plant Conservation Alliance 2006, USDA Nat. Resour. Conserv. Serv. 2007). Japanese honeysuckle spreads by vegetative runners, underground rhizomes, and seed dispersal, particularly by birds. It quickly becomes established and crowds out native plants, drastically influencing understory diversity.

Non-Native Invasive Plants and Site Conditions

Site Class

A site's productivity benefits exotics and their native competitors alike. How a plant captures and utilizes soil resources relative to its competitors, determines the extent of its presence now and into the future (Newsome and Noble 1986).

There was a significant relationship between multiflora rose and and site quality, but not for non-native bush honeysuckles or Japanese honeysuckle (Table 3). Invasive plants are known to be competitive on high-quality sites (Davis and Pelsor 2001) so the results partially support this idea. However, the collinearity between high site quality and present- or former human habitation (the primary influence behind the initial establishment of invasives) should be taken into account.

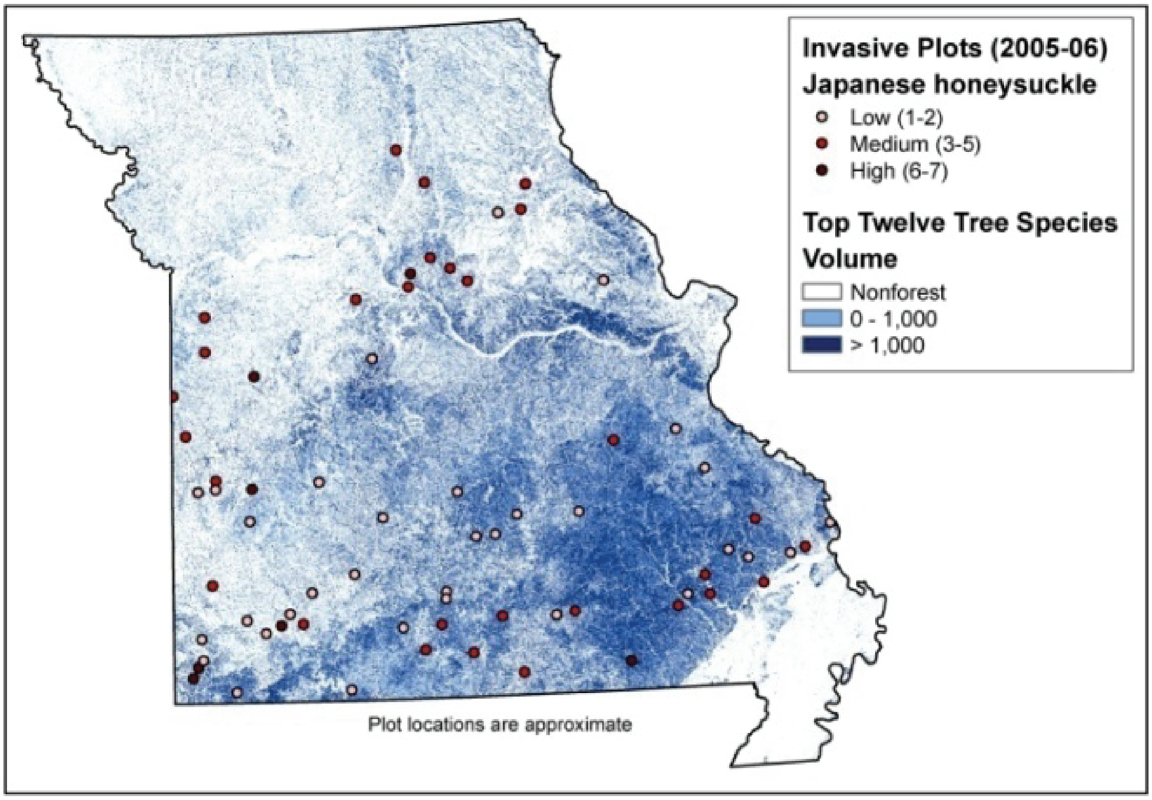

Figure 7.—Distribution of plots with Japanese honeysuckle present, by cover class, Missouri 2005-2006. The blue shades in the background represent the volume (in ft^3 ac^{-1}) of the top 12 tree species in the Upper Midwest.

Table 3.—Non-native invasive plant presence as a function of site class category, Missouri 2005-2006. Numbers in parentheses are the percentages for that site class category. (Multiflora rose: X^2 = 9.185, d.f. = 2, p=0.01013; Non-native bush honeysuckles: X^2 =6.45, d.f. = 2, p=0.0398; Japanese honeysuckle: X^2 = 0.9481, d.f. = 2, p=0.6225). Low = 0-50 ft (0-15.2 m) at 50 years, Medium 51-70 ft (15.2-21.3 m), and High = 71+ ft (21.3+ m).

	Low	Medium	High
Multiflora rose			
Yes	109 (34)	228 (34)	120 (44)
No (Cover class = 0)	210 (66)	444 (66)	153 (56)
Non-native bush honeysuckles			
Yes	31 (10)	46 (7)	12 (4)
No (Cover class = 0)	288 (90)	626 (93)	261 (96)
Japanese honeysuckle			
Yes	14 (4)	39 (6)	16 (6)
No (Cover class = 0)	305 (96)	633 (94)	257 (94)

Table 4.—Non-native invasive plant presence as a function of aspect category, Missouri 2005-2006. Numbers in parentheses are the percentages for that aspect category. (Multiflora rose: X^2 = 10.63 d.f. = 2, p=0.004914; Non-native bush honeysuckles: X^2 = 2.882 d.f. = 2, p=0.2367; Japanese honeysuckle: X^2 = 8.192 d.f. = 2, p=0.01664)

	Level	North-East aspects	South-West aspects
Multiflora rose			
Yes	125 (44)	168 (33)	164 (34)
No (Cover class = 0)	157 (56)	337 (67)	313 (66)
Non-native bush honeysuckles			
Yes	18 (6)	30 (6)	41 (9)
No (Cover class = 0)	264 (94)	475 (94)	436 (91)
Japanese honeysuckle			
Yes	25 (9)	22 (4)	22 (5)
No (Cover class = 0)	257 (91)	483 (96)	455 (95)

Aspect

Given the patterns of rainfall and insolation, aspect is a surrogate for available soil moisture. This study searched for any relationship between aspect and the presence of the top three NNIPs.

Aspect significantly influenced location and extent of multiflora rose and Japanese honeysuckle in Missouri (Table 4); both species were more likely to be found on level aspects.

Physiographic Class Code

The physiographic class code is a variable that represents the general effect of landform, topographic position, and soil on the moisture available to trees (Miles and others 2001). The bulk of the plots in this study are located on rolling uplands or dry slopes (Table 5). These results partially support Rejmánek (1989), who concluded that plant communities in mesic environments were more invasible than communities in more extreme environments. Xeric sites were difficult for germination and seedling survival ("abiotic resistance") and hydric sites were often light-limited (from the point of view of invasives) due to the rapid growth of the species on site ("biotic resistance") (Rejmánek and others 2004).

While all three species appeared to be correlated with mesic sites, broad physiographic class codes (hydric, mesic, and xeric) were significantly related only to the presence of multiflora rose and Japanese honeysuckle, not to non-native bush honeysuckles (Table 6). Japanese honeysuckle is known to be a vigorous competitor in mesic and riparian areas (Ohio Dept. of Nat. Resour. 2001). Multiflora rose is tolerant of a wide range of site conditions, including xeric sites (Missouri Department of Conservation 1997).

Disturbance Factors and Non-Native Invasive Plants

NRS FIA crews note disturbances that have occurred on the Phase 2 plots since the previous inventory. It is possible to record up to three disturbance factors, with priorities assigned in the order of estimated impact on the plot. For the plots sampled in 2005 and 2006, the previous inventory was in 2000 and 2001, respectively. In this study, disturbance factors were compared to the most prominent invasive species on each plot. There was no significant relationship between the invasive species and disturbance types (X^2 = 39.98, d.f. = 80 (p=0.9999)).

Table 5.—Number of plots by number of non-native invasive plants per plot and physiographic class code, Missouri 2005-2006

	Number of invasive plants present on plot				
Plot	0	1	2	3	4
HYDRIC	1	0	1	0	0
Bays, Wet Pocosins	0	0	0	0	0
Beaver Ponds	0	0	0	0	0
Swamps, Bogs	0	0	0	0	0
Other Hydric	0	0	0	0	0
MESIC	291	247	65	6	1
Broad Floodplains Bottomlands	23	1	1	0	0
Flatwoods	15	17	2	0	0
Moist Slopes and Coves	7	7	1	0	0
Narrow Floodplains Bottomlands	34	31	8	0	0
Rolling Uplands	209	190	52	6	1
Small Drains	1	0	1	0	0
Other Mesic	2	1	0	0	0
XERIC	443	177	28	5	1
Deep Sands	1	1	1	0	0
Dry Slopes	359	143	19	5	0
Dry Tops	78	25	4	0	1
Other Xeric	5	8	4	0	0

Table 6.—Non-native invasive plant presence as a function of broad physiographic class codes, Missouri 2005-2006. Numbers in parentheses are the percentages for that physiographic class code. (Multiflora rose: X^2 = 62.46, d.f. = 2, p=0.000*10-14; Non-native bush honeysuckles: X^2 = 5.12, d.f. = 2, p=0.0773; Japanese bush honeysuckle: X^2 = 8.346, d.f. = 2, p=0.0154)

	Hydric	Mesic	Xeric
<u>Multiflora rose</u>			
Yes	1 (50)	287 (47)	169 (26)
No (Cover class = 0)	1 (50)	321 (53)	485 (74)
<u>Non-native bush honeysuckle</u>			
Yes	0 (0)	53 (9)	36 (6)
No (Cover class = 0)	2 (100)	555 (91)	618 (94)
<u>Japanese honeysuckle</u>			
Yes	1 (50)	36 (6)	32 (5)
No (Cover class = 0)	1 (50)	572 (94)	622 (95)

Table 7.—Presence of the three most prominent non-native invasive plants in Missouri by overstory basal area, in square meters per hectare, 2005-2006. Numbers in parentheses are the percentages for that basal area interval.

Basal area, in m^2 ha^{-1}	0+ thru 12	12+ thru 18	18+ thru 24	24+ thru 48	Total	Chi squared
All plots	364 (29)	625 (50)	248 (20)	16 (1)	1253	
No invasives present	165 (23)	390 (54)	159 (22)	12 (2)	726	X^2 = 34.64, d.f.= 3, p=0.000
Multiflora rose	170 (37)	203 (45)	77 (17)	4 (1)	454	X^2 = 24.84, d.f.= 3, p=0.000
Non-native bush honeysuckles	34 (38)	34 (38)	21 (24)	0 (0)	89	X^2 = 7.305, d.f.= 3, p=0.06278
Japanese honeysuckle	24 (35)	33 (48)	12 (17)	0 (0)	69	X^2 = 2.033, d.f.= 3, p=0.5656

Overstory Basal Area

In order to comprehend the degree of overstory competitive influence on understory flora and the residual impact of past disturbance or management practices, we examined the relationship between NNIPs and overstory basal area. A vigorous tree overstory has the potential to suppress the growth and vigor of a plant understory. Our hypothesis was that low basal areas reflect minimal competition for light, water, and nutrients, but also could represent the lingering effects of past disturbances, such as wind damage, insect or disease attack, or recovery from overstory removal, or agricultural clearing.

The comparison of invasive presence by overstory basal area found only a significant difference between all plots and those plots with multiflora rose (Table 7), which appeared to benefit from reduced overstory basal area. Whether this result derives from the past disturbance events that might be associated with lower basal areas or the specific microenvironments associated with such open canopies, we cannot say.

Non-Native Invasive Plants and the Influence of Roads

Highways and roads are the life's blood of the U.S. society and economy. The "car culture" that developed after the Second World War defined the pattern of settlement, commuting, and recreation activities that have left an indelible stamp on our landscape. Along with human habitation and recreation came non-native invasive species. Either deliberately or inadvertently, roads became conduits for these exotics to enter and alter natural ecosystems. Studies have found a relationship between distance to road and prevalence of exotic species (e.g., Watkins and others 2003). The influence is most pronounced within 30 meters of a road. Forman and Alexander (1998) could not document many cases where species spread more than 1,000 meters feet because of a road. For these reasons, this study assumed that the roads represent surrogates for human activity, rather than conduits for invasive exotics in and of themselves.

Table 8 displays the distribution of all plots, plots with no invasives, and the top three exotics by distance from the nearest road. At first, comparing relative proportions to all plots and plots without invasives did not seem to reveal a substantial difference. A majority of plots, regardless of invasive presence, were 328 to 1640 feet from the nearest road, and plots with invasives species displayed approximately the same proportion. Further analysis found, however, that invasive absence, multiflora rose, and Japanese honeysuckle were significantly related to the road variable. The distance influence is more dramatic at the greater distances, where the invasive species' proportions drop off while the proportion of plots with no invasives present increased in proportion to all of the plots in the study.

Table 8.—Presence of the three most prominent non-native invasive plants categorized by distance from the nearest road, in feet, Missouri, 2005-2006. Numbers in parentheses are the percentages of the species for that distance interval.

	Distance from road (feet)						
	0	0+ thru 328	328+ thru 1640	1640+ thru 3280	3280+ thru 9840	Total	Chi squared
All plots	4 (0.32)	249 (20)	721 (57)	233 (18)	57 (4.5)	1264	
No invasives present	0 (0)	129 (18)	406 (55)	149 (20)	50 (6.8)	734	X^2 = 34.35, d.f.= 4, p=0.000
Multiflora rose	4 (0.9)	102 (22)	272 (60)	72 (16)	7 (1.5)	457	X^2 = 27.19, d.f.= 4, p=0.000
Non-native bush honeysuckles	0 (0)	24 (27)	45 (51)	18 (20)	2 (2.2)	89	X^2 = 4.827, d.f.= 4, p=0.3055
Japanese honeysuckle	0 (0)	21 (30)	41 (59)	7 (10)	0 (0)	69	X^2 = 10.58, d.f.= 4, p=0.03165

DISCUSSION

This study examined patterns of distribution and relationships with selected forest and site characteristics for 25 exotic species/species groups of interest in Missouri. Only three species—multiflora rose, non-native bush honeysuckles, and Japanese honeysuckle—were found in any number among the 1264 total plots. There seemed to be a logical connection with the study area and the potential for invasives. Oaks, the predominant forest type in Missouri, are mid-shade tolerants and rely upon disturbance to maintain their position in most parts of the genus' range (Johnson and others 2002)[5]. Missouri, particularly the Ozark Plateau, had a long history of natural and anthropogenic disturbances (Beilmann and Brenner 1951, Guyette and others 2002). Given the history of natural and human-caused disturbance and forest types whose shade tolerance means the growing space might not be completely occupied, we expected to find multiple relationships between NNIP and forest and site characteristics.

We found some relationship between multiflora rose and non-native bush honeysuckle presence and site quality; the species benefitted from higher site index values. The presence of multiflora rose and Japanese honeysuckle was found to be significantly related to level aspects. When we looked at physiographic class code for any influence of topography (and—by extension—water availability/site productivity) upon NNIP presence, we found a significant relationship with multiflora rose and mesic/xeric sites and Japanese honeysuckle and hydric/mesic plots plots. Relatively few of the target species were found in hydric systems, a function of the species list and the emphasis on forested lands in Missouri. When looking at disturbance, we found that multiflora rose significantly benefitted from lower overstory basal areas, but not the other species. Another measure of disturbance, distance to roads, was a significant, negative influence on multiflora rose and Japanese honeysuckle presence.

These results are not surprising; invasive species are known to thrive on sites with more available resources (Richardson and Pyšek 2006). In most parts of Missouri, level sites are more productive than those areas with steep slopes (but not always in the Ozarks; see Lawrence and others 2002). The challenge is separating the human influence from the ecological one. One could easily argue that our results reflect the heavily disturbed nature of Missouri's second- and third-generation forests, which either came back upon

[5]In fact, the lack of disturbance is resulting in a shift in species composition of regeneration in oak forests throughout the genus' range (Moser and others 2006).

abandoned farmland or pasture or were influenced by heavily disturbed adjacent land. The characteristics of the landscape that we found to influence invasive species presence may also be a significant influence on homestead choice by settlers. Even our disturbance measures, lower basal area and proximity to roads, could as easily reflect the human hand that originally placed the plants in that location as the microsite attributes that allowed them to subsequently thrive.

A posteriori analysis of invasive species at one point in time is usually not sufficient to evaluate trends in regeneration, expansion, or growth (Rejmánek 1989). The FIA database tracks disturbance and silvicultural treatments, but only in the interval since the previous inventory. The anthropogenic activities that resulted in the establishment of these non-native invasive species likely occurred many years ago. We are conducting a region-wide analysis, but repeated measures on a wide scale will be necessary to verify trends that, up to now, are little more than anecdotal in Missouri.

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INVESTIGATING THE RELATIONSHIP BETWEEN BOLE SCORCH HEIGHT AND FIRE INTENSITY VARIABLES IN THE RIDGE AND VALLEY PHYSIOGRAPHIC PROVINCE, WEST VIRGINIA

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Abstract.—Prescribed fires are carried out on the George Washington National Forest (GWNF) in West Virginia to promote long-term resource and social values, including tree regeneration, improving wildlife habitat and aesthetics, and maintenance of low woody fuel loading. Prescribed fire programs have increased on the GWNF over the past 20 years. Although prescribed fire is widely used on the GWNF, methods and techniques for monitoring fire behavior are still in the early stages of development. As part of a larger study to assess the effects of prescribed fire on invasive species in eastern West Virginia, we used simple linear correlation and regression analysis to investigate the relationships between plot-level 3-year post-fire bole scorch height parameters, fire temperature as estimated by thermocouple probes, litter consumption, and sapling mortality to better understand and predict fire effects in mixed-oak and oak-pine forests. We collected information on these parameters as they were observed on 36 research plots in an area where a prescribed fire had been applied in the Ridge and Valley physiographic province of eastern West Virginia. The prescribed burn totaled 313.6 ha and was conducted in March 2004. Neither overstory nor sapling bole scorch height variables were significantly related to thermocouple temperature measurements recorded at five locations on a southwest-facing slope ($\alpha = 0.05$). The sum of the sapling scorch heights was significantly related to litter consumption, but accounted for only 11 percent of the variation. However, all bole scorch height variables were significantly related to sapling mortality one growing season after the fire. This result further illustrates the usefulness of scorch height as an estimator of relative fire intensity, and provides a useful prediction model for xeric mixed-oak and oak-pine fire managers.

INTRODUCTION

Prescribed fire is primarily used on West Virginia's George Washington National Forest (GWNF) to manage areas unsuitable for timber production. These sites are often characterized by infertile soils, steep/rocky slopes, noncommercial/low-value species mixtures, or pine-oak stands in general (USDA Forest Service 1993). The fires are applied to promote long-term resource and social values such as maintenance of low woody fuel loading, aesthetics, tree regeneration, and increased abundance of such understory plants are valuable for wildlife forage as blueberries (*Vaccinium* spp.), huckleberry (*Gaylussacia baccata*), scrub oak (*Quercus ilicfolia*), and various grasses. Since the mid- to late-1980s, the extent of these fires has increased quite dramatically (Fig. 1). During the 1980s, GWNF managers treated, on average, 37.2 hectares/year, compared to 877.2 hectares/year in the 1990s and 2,097.0 hectares/year this decade. Those averages equate to an astounding 2,240 percent freom the 1980s to the 1990s, and a 140 percent increase from the 1990s to the 2000s.

Several studies have examined fire behavior in a number of various regions. However, fire behavior-related studies in the Appalachian region are limited (Franklin and others 1997, Clinton and others 1998, Vose

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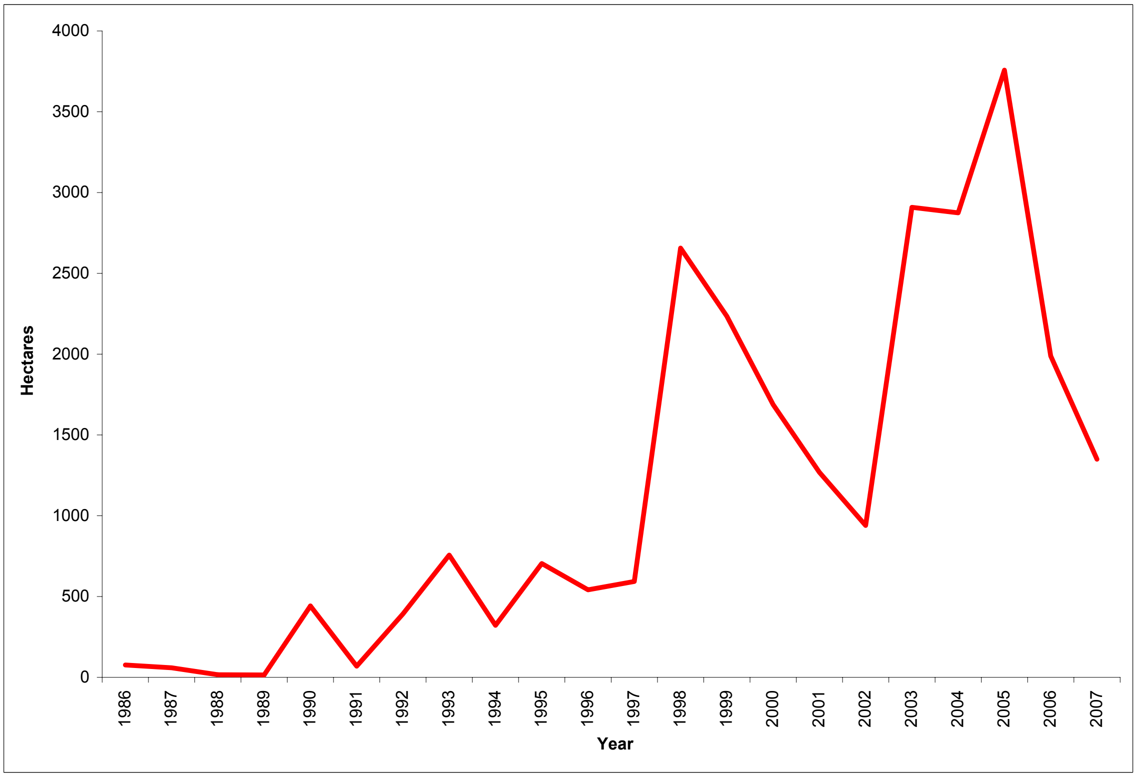

Figure 1—Area treated with prescribed fire by year on the George Washington National Forest.

and others 1999, Iverson and others 2004). Although prescribed fire is widely used on the GWNF, methods and techniques for monitoring fire behavior are still in the early stages of development.

Bole scorch height, otherwise known as stem-bark char or height of bole blackening, has been proven to be a significant predictor of post-fire mortality in various forest types (Loomis 1973, Regelbrugge and Conrad 1993, Regelbrugge and Smith 1994, Wyant and others 1986). It has also been proven to be highly correlated with areal percent canopy scorch and top-kill of individual trees (Regelbrugge and Smith 1994). Although bole scorch height underestimates flame length in prescribed burns (Cain 1984), these findings indicate that it can be used to estimate relative fire intensity at the stand level.

As part of a larger study to assess the effects of prescribed fire on invasive species in eastern West Virginia, we investigated the relationship between plot-level 3-year post-fire bole scorch height parameters (independent variables) and other fire intensity variables to better understand and predict fire effects in mixed-oak and oak-pine forests. A better understanding of the role of fire in determining the structure and composition of xeric mixed-oak and oak-pine forests of the Ridge and Valley physiographic province will enhance management efforts to sustain these forests.

We focus on the relationships between measured variables and the usefulness of these parameters for: predicting changes in stand structure. Three relationships/predictions will be evaluated, including (1) litter consumption as a function of scorch height; (2) thermocouple estimated fire temperature as a function of scorch height; and (3) sapling mortality as a function of scorch height. The intent of this analysis is to evaluate whether these quick, simple, and inexpensive field measurements can help characterize prescribed fire behavior and its short-term effects on forest structure and composition. We expect increasing litter consumption, thermocouple temperature, and sapling mortality with increasing bole scorch height.

METHODS

Study Site

Our research was conducted at Dunkle Knob, located on the North River Ranger District (formerly the Dry River Ranger District) of the GWNF, Pendleton County, WV (38° 37′ N, 79° 14′ W). Our study area included 313.6 ha and is composed of xeric mixed-oak and oak-pine communities. The area is within the Ridge and Valley province and is in the rain-shadow of the Allegheny Mountains, which causes a climate that is much drier than the rest of the state (Core 1966). The area is characterized by an average annual precipitation of 82 cm, an average annual temperature of 10.9 °C, and a growing season of approximately 144 days (Estepp 1992). Forests of the region can be characterized as being part of the former oak-chestnut cover type (Braun 1950).

The topography is highly dissected with slopes ranging from 6 to 70 percent. Elevation ranges from 573 to 848 m. The predominant soil type is of the Berks-Weikert association. Soils are loamy-skeletal, mixed, Dystrochrepts formed from acidic shale, siltstone, or sandstone bedrock. The soils are droughty and infertile and often contain numerous rock outcroppings (Estepp 1992).

The Dunkle Knob area was purchased by the USDA Forest Service in 1923. There have been no documented fires in the Dunkle Knob area from its purchase date up to the time of the prescribed fire (Marsh 2005). Dunkle Knob was treated with a prescribed fire on March 29, 2004. Air temperatures ranged from 11 to 21 °C and relative humidity ranged from 29 to 76 percent. Winds were primarily from the northwest and southeast at a speed of 2-10 km/H. The interior of the mountain was ignited in a northeast-southwest pattern from top to bottom by a helicopter dropping delayed aerial ignition devices. The perimeter, established using existing roads and limited new fire line construction, was ignited by personnel on the ground using drip torches (Marsh 2005).

Pre-fire (2003) total basal area for the overstory (trees ≥12.7 cm diameter at breast height [d.b.h.]) averaged 20.8 m^2/ha, and increased to 23.0 m^2/ha by 2007. Chestnut oak (*Quercus prinus*), table mountain pine (*Pinus pungens*), and Virginia pine (*P. virginiana*) made up 66.5 percent of the overstory basal area in 2007.

Field Methods

Thirty-six circular 0.05-ha overstory plots were randomly established at the Dunkle Knob study site during the summer of 2003 (pre-fire). Eighteen plots were randomly established on northeast (315-235°) and southwest (236-314°)-facing slopes. Within each aspect class, nine plots were established above and below 748 m elevation. To aid in future relocation, sample points were located with a global positioning system (GPS) and a piece of steel rebar was driven into the ground at plot center. In addition, plot boundaries were flagged.

Each plot was inventoried in the summers of 2003 (pre-fire), 2004 (one growing season post-fire) and 2007, three full growing seasons after the fire. All overstory trees (d.b.h. >12.7 cm), both living and dead, were tallied. Each tree was identified to species (although a small number of dead trees could not be positively identified), and crown class was recorded. Stem diameter was measured to the nearest 0.1 cm using a diameter tape. During the 2007 inventory, bole scorch height, defined as height of the highest point of bole blackening on the uphill face of the tree (Regelbrugge and Smith 1994), was measured to the nearest 15 cm using a height pole. The sapling layer (all trees 2.54 cm ≤ d.b.h. ≤ 12.6 cm) was sampled using a circular 0.01-ha plot located at the center of each overstory plot (n = 36). All saplings were identified to species and d.b.h. Bole scorch height on saplings was also recorded as described above.

Also within each overstory plot, 1 m^2 circular plots were established at 12.06 m from the overstory plot center in each of the four cardinal directions (n = 144). These were primarily for understory vegetation measurements; however, litter layer (Oi) depth was measured to the nearest 0.1 cm at the west end of each plot using a ruler in 2003 (pre-fire) and 2004 (3-4 months post-fire).

On five south-facing overstory plots, 9.14 m^2 square sampling plots were established. On these plots, the prescribed fire itself was monitored using a network of thermocouple probes. These sample points were selected due to logistical considerations and the expectation that the prescribed fire would be the most intense on southerly aspects (Marsh 2005). At the corners and at the center of these square plots, 25 cm thermocouple probes were installed and HOBO® data loggers (Onset Computer Corporation, Bourne, MA) were buried just below the surface in a manner similar to that of Iverson and others (2004) and set to record thermocouple temperature at 4-second intervals the day of the prescribed fire. All data loggers were collected immediately following the treatment. It is well known that Type K thermocouple probes cannot record flame or air temperature around the probe during a prescribed fire because of the lag time of the probes and the relatively short duration of the most intense heating (Iverson and others 2004). However, it was our desire to use a small sample of thermocouple probe temperature data to characterize fire behavior on what we believed would be the most intense area of the fire, and to assess its usefulness for predicting fire effects.

Analytical Methods

Pre- and post-fire litter depth (LD) measurements were averaged for each overstory plot (n = 4), and litter consumption was quantified by the average percentage change in these values (n= 36). Litter consumption was calculated using the equation:

$$Litter\,Consumption = \left(\frac{\left(LD_{post} - LD_{pre}\right)}{LD_{pre}} \right) * 100$$

Scatter plots were used to graphically examine all relationships for linearity, as well as any potential non-linear relationships. Following graphical examination, simple linear correlation and regression analysis were performed to examine the relationship between litter consumption (dependent) and both overstory and sapling bole scorch height measures (mean and sum) (independent) for all plots. The sum of hardwood tree heights is commonly used as a measure of hardwood competition in young southern pine plantations. Similarly, we tested the sum of the scorch heights as an independent variable that combines the number of stems scorched and degree of charring to determine its usefulness as a surrogate for fire behavior.

The analysis was also performed separately for mostly scorched plots. In this study, mostly scorched plots are defined as plots in which ≥50 percent of the overstory trees were scorched. This separate analysis was performed in hopes of reducing within-plot scorch height variability. This method reduced this variability considerably in a pilot study of plot level bole scorch height against temperature-sensitive paint used to estimate fire temperature from another prescribed fire in a mixed-oak stand in the Ridge and Valley province[2].

Linear correlation and regression were also used to examine the relationships between recorded thermocouple temperature (dependent) and bole scorch height parameters.

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[2]Data on file with the USDA Forest Service, Northern Research Station, Parsons, WV.

Table 1.—Average scorch height parameters(cm) by stratum

Stratum	Mean	Sum
Overstory	56.01	1450.41
Sapling	38.37	286.08

Both means were significantly different between strata at α = 0.05.

Table 2.—Relationships between bole scorch height variables (cm) and litter consumption (%) for all plots

Stratum	Variable	r	R^2	P
Overstory	Mean	0.20	0.04	0.253
	Sum	0.14	0.02	0.407
Sapling	Mean	0.29	0.09	0.128
	Sum	0.33	0.11	0.049*

*Indicates significance at α = 0.05

To better understand how post-fire stand structure attributes were influenced by surrogates of fire intensity, a third correlation/regression analysis was performed to observe how the change in the number of understory living saplings (percent mortality) varied with plot-level bole scorch height variables.

All statistical analyses were performed using SAS 9.1 software (SAS Institute, Cary, NC, 2003), with significance determined at an $\alpha = 0.05$. Effects of independent variables were assessed using the General Linear Model procedure. Mean comparisons were evaluated with paired t-tests. The DFFITS procedure was used to examine plot data and identify influential observations (outliers). The SAS DFFITS procedure identified one plot as a statistical outlier. Therefore this plot was removed from the analyses. Interestingly, this was the only plot in the study area in which the overstory was dominated by pitch pine (*Pinus pungens*) (>50 percent of the overstory basal area). Both average and sum of the scorch heights on this plot were much greater than on others.

RESULTS AND DISCUSSION

Litter Consumption

Immediately following the prescribed fire, litter depth differed significantly from pre-fire conditions. The fire, on average, resulted in a 49.5 percent decrease in litter depth (2.14 cm in 2003 compared to 1.08 cm in 2004). Average 3-year post-fire bole scorch height variables were significantly different between the overstory and understory strata based on paired t-tests. Loucks and others (2004) found that mean scorch heights increased with larger diameter classes in an Appalachian hardwood forest in Kentucky. Similarly, our study showed means that were significantly higher for the overstory stratum (Table 1). These scorch height differences suggest that researchers or managers interested in measuring scorch height should also stratify their sample by these forest layers.

Neither of the overstory stratum independent variables (mean and sum of the scorch heights) could effectively predict litter consumption (Table 2). The sum of the sapling scorch heights, however, proved to be a significant litter consumption predictor. Unfortunately, the model can account for omly 11 percent

Table 3.—Relationships between bole scorch height variables (cm) and litter consumption (%) for plots with ≥50 percent of the trees scorched (n = 18)

Stratum	Variable	r	R^2	P
Overstory	Mean	0.22	0.05	0.393
	Sum	0.10	0.01	0.634
Sapling	Mean	0.35	0.12	0.168
	Sum	0.45	0.20	0.060

Table 4.—Relationships between bole scorch height variables (cm) and fire temperature (°C) for 5 plots fitted with thermocouples

Stratum	Variable	r	R^2	P
Overstory	Mean	0.62	0.39	0.264
	Sum	0.70	0.50	0.184
Sapling	Mean	0.04	0.002	0.940
	Sum	0.14	0.02	0.823

of the variation in litter consumption. More intricate fuel measurements (e.g., fuel transects and moisture content) may show stronger relationships to the measured variables than simple percentage change in litter depth. Mass changes in the litter layer may alter ecosystem functions, but can be time-consuming to measure. Developing efficient methods for estimating such changes would be helpful to forest managers. The fire effects on the litter layer were similar to the work of Brown and others (1991) and Elliot and others (2002).

Contrary to our expectations, the results were similar when the analysis was restricted to plots in which greater than 50 percent of the trees were scorched (Table 3). Even though we found a positive linear correlation, there was little evidence that any measure of scorch height was a useful predictor of litter consumption, due to the large amount of unexplained variation in the model. The most promising explanatory variable in this restricted analysis was the sum of the sapling scorch heights ($P = 0.060$). We suspect that the weak correlation between these variables is due to the litter layer itself. That is, given the thin pre-fire litter layer (2.14 cm on average) plots experiencing even the modest intensity would likely lose nearly their entire litter layer. Future efforts to develop easy-to-measure predictor variables to estimate litter consumption should narrow the ecological amplitude of the explanatory variables to potentially improve model performance.

Thermocouple Temperature

Although we found a general positive relationship between scorch height and thermocouple temperature, there was little evidence of a useful predictive relationship (Table 4). When compared to litter consumption predictions, R^2 values were, in general, higher for overstory scorch height-based thermocouple temperature predictions. This value is larger, however, probably because only a small number of points could be used to examine the relationships between scorch height and thermocouple temperature.

It should be emphasized that our thermocouple temperatures used in the analysis were the average of five thermocouple probes on each plot. Due to the limitation of such instrumentation, averaging probe

Table 5.—Sapling mortality (%) models and associated statistics

Model	r	R^2	SEE	P
%Mort.= 4.03 + 0.39(mean overstory scorch height [cm])	0.79	0.63	4.37	<0.001*
%Mort.= 9.75 + 0.01(sum of overstory scorch heights [cm])	0.69	0.47	4.89	<0.001*
%Mort.=10.96 + 0.39(mean sapling scorch height [cm])	0.42	0.18	7.28	0.010*
%Mort.= 16.41 + 0.03(sum of sapling scorch heights [cm])	0.44	0.19	5.87	0.008*

*Indicates significance at α = 0.05

temperature may mask significant spatial variability among fire intensity throughout the sample area, ultimately weakening the relationship. Despite our results, we speculate that useful predictive relationships between thermocouple probe temperatures and fire effects could be developed if more spatially limited procedures were utilized. Employing more intensive sampling would likely limit bias and produce more indicative and statistically significant results as well. However, the time-consuming nature of using thermocouple probes combined with their potentially limited spatial extrapolations may ultimately restrict their usefulness by managers.

Sapling Mortality

Total pre-fire number of living saplings averaged 1000 trees per hectare (TPH), compared to 725 TPH in 2004. These values were significantly different (P < 0.001). Chestnut oak, pignut hickory (*Carya glabra*), Virginia pine, and striped maple (*Acer pensylvanicum*) made up 53.7 percent of the number of saplings in 2007.

There was ample evidence of a relationship between scorch height and sapling mortality induced by the prescribed fire. All overstory and sapling layer scorch height variables were significant predictors of sapling mortality (Table 5). We plan further analysis to assess species-specific predictive relationships. Average overstory bole scorch height provided the strongest relationship and accounted for 63 percent of the variation in sapling mortality (Fig. 2). By contrast, Regelbrugge and Smith (1994) found that the average scorch height accounted for 96 percent of the variation in the percentage of the number of fire-killed trees. However, their study was conducted in the aftermath of a 1900 ha wildfire which exhibited greater amplitude in scorch height and fire severity than the Dunkle Knob prescribed fire we monitored. They also chose stands with both low and high fire severity to provide a wide range of fire intensity and subsequent effects. Our results further illustrate the usefulness of this relationship even when conditions are much more homogenous.

When the sapling mortality analysis was restricted to mostly scorched plots, relationships/models were not nearly as sound. Therefore, these results were not reported.

CONCLUSIONS

Our results indicate that, at the plot level, the measured 3-year post-fire overstory and sapling bole scorch height variables (mean and sum) are not significantly correlated to litter consumption or thermocouple temperature. The results do, however, indicate that sapling mortality (one growing season post-fire) is a function of the tested bole scorch height parameters, with the strongest independent variable being average overstory scorch height. This finding further illustrates the usefulness of scorch height as an estimator of relative fire intensity and fire effects, and will allow for an examination of how relative fire intensity relates to changes in exotic-invasive plant populations (the larger study).

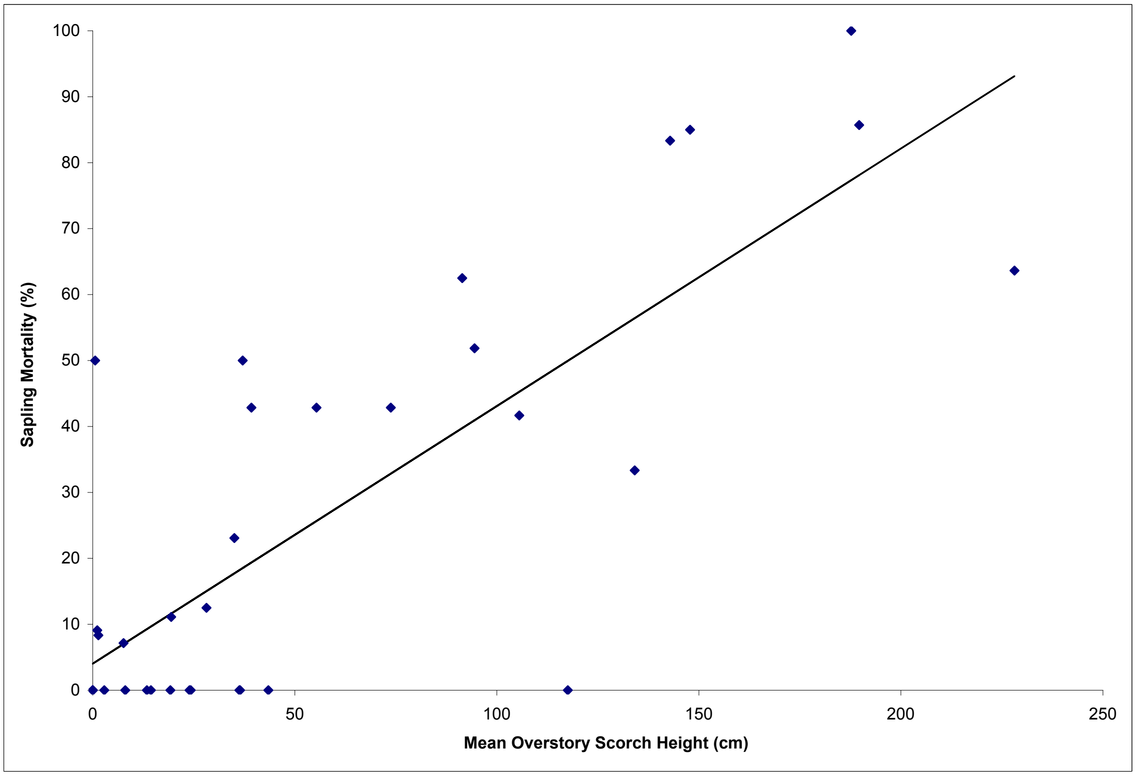

Figure 2.—The relationship between mean overstory scorch height (cm) and sapling mortality (%).

The relationship between average scorch height and sapling mortality also has the potential to be very useful for xeric mixed-oak and oak-pine fire managers. The mean overstory scorch height model indicates that 50 percent mortality can be expected at an average overstory scorch height of just over 1 m. An average overstory scorch height just less than 2 m would result in about 75 percent sapling mortality. An average overstory scorch height of about 2.5 m would likely result in 95 percent mortality. This model can be used to make a quick and inexpensive assessment of fire-induced mortality in areas where pre- and post-fire saplings were not sampled. Managers could also use the information to adjust ignition patterns to alter the potential sapling mortality in similar xeric mixed-oak and oak-pine prescribed fires.

However, the model does have its limitations. It has not been tested against independent data, and should therefore be considered preliminary. Nonetheless, we do feel that the model will provide a sensible estimate of plot-level sapling mortality (1 year post-fire). Use of the model should be limited to xeric mixed-oak and oak-pine forests of the Ridge and Valley physiographic province. Also, due to the statistical outlier and its removal, model predictions should not be applied when pitch pine makes up a high percentage (>50 percent) of the basal area in the area being burned.

Further analysis of existing information about both dependent and independent variables is planned to better understand the relationships examined. For example, measures of scorch height models of mortality may be different for disparate species such as red maple (*Acer rubrum*) and chestnut oak. Also, because topography is related to scorch height (Loomis 1973), the effect of slope percent, aspect, elevation, slope position, landform shape, etc. should be examined. Loucks and others (2004) found higher scorch heights in more xeric locations. Logistic or multiple regression models may provide improved predictions by incorporating these and other influential variables.

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SEED BANK EMERGENCE FOLLOWING PRESCRIBED BURNING IN THE OZARK HIGHLANDS

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Abstract.—Much information is available describing the effects of fire on the survival, growth, and sprouting ability of hardwood stems. This information is generally used for predicting the response of established trees and advance reproduction to various burning treatments during the process of regenerating new stands. This study describes an often overlooked component of reproduction—the soil seed bank. The seed bank consists of stored seeds that are freshly fallen or older seeds that are viable but dormant. In order to predict stand-level regeneration treatments that incorporate burning, accurate assessment of the effects of burning on this source of regeneration is important. The number of tree species germinating from the seed bank was very low in both pre- and post-burn samples. The burning treatment increased species richness and abundance. Shifts in species presence/absence were also noted, with graminoid species more prevalent after burning.

INTRODUCTION

Historically, many forests in the Ozark Mountain region of Arkansas had relatively large representation of oak stems (*Quercus* spp.) in the overstory with open midstory and understory strata that were described as having park-like appearances (Park 1955). The maintenance of these forest stand conditions has been linked, at least in part, to fires that frequently burned these areas. Mean fire return intervals ranged from 3 to 7 years in many parts of this region (Guyette and Spetich 2003). Oak species are known for their resistance to fires even at young ages due to thick bark, a propensity to sprout, and hypogeal germination that protects the cotyledons during the first year of establishment. However, due to long-term fire suppression, the current forest conditions commonly have a resurgence of the under- and midstory strata, which are composed of shade-tolerant non-oak species (Soucy and others 2005). Difficulties in regenerating oak species have ensued, prompting a new look at the importance of periodic fires in maintaining oak communities.

Prescribed burning is the purposeful and intentional application of fire to reduce fuel loadings and control competing vegetation. Numerous scientific studies have documented its utility in significantly improving the composition of oak (Adams and Rieske 2001, Barnes and Van Lear 1998) by reducing the quantity of fire-sensitive species and improving the seedbed conditions for oak species. Prescribed fires often are advocated where tolerant woody species like blackgum (*Nyssa sylvatica* L.), red maple (*Acer rubrum* L.), and black cherry (*Prunus serotina* Ehrl.) suppress or intensively compete with established oak stems (Brose and others 1999). Both dormant-season and growing-season fires can be successful in reducing non-oak competitors.

The soil seed bank is the storehouse for newly fallen seeds and older but viable seeds that have remained dormant. For some woody species, seed viability is limited to one season, meaning they must germinate immediately in the fall following seed fall (e.g., white oak [*Q. alba* L.]) or the following spring (e.g., northern red oak [*Q. rubra* L.]; privet [*Ligustrum sinense* L.]; loblolly pine [*Pinus taeda* L.]). Others are capable of "carry-over", meaning seeds can accumulate over time ranging from 2 years (e.g., red maple)

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Table 1.—Pre-burn overstory species composition for two upland oak stands in the Arkansas Ozark Highlands

	Falling Water		Meadows Knob	
Species	Dormant Season	Growing Season	Dormant Season	Growing Season
	----------------Percent of basal area----------------			
Quercus alba	35.9	35.2	34.4	44.2
Quercus rubra	16.3	30.8	14.8	31.2
Quercus velutina	14.1	4.4	34.4	11.7
Nyssa sylvatica	13.0	9.9	4.9	6.5
Carya spp.	10.9	7.7	4.9	1.3
Quercus stellata	5.4	6.6	0.0	3.9
Pinus echinata	2.2	2.2	0.0	0.0
Acer rubrum	2.2	1.1	3.3	1.3
Prunus serotina	0.0	1.1	3.3	0.0
other	0.0	1.1	0.0	0.0

to a decade (e.g., yellow-poplar [*Liriodendron tulipifera* L.]) to a century or more (e.g., pin cherry [*Prunus pensylvanica* L.])(Tierney and Fahey 1998).

To the best of our knowledge, however, there are limited studies focusing on the impacts of fire on the soil seed bank. Some studies have used simulated fires or artificial seeding to explore some of these effects. For example, Cain and Shelton (1998) demonstrated reduced germination capacity for acorns placed at the surface litter layer, but no effect on acorns located at the mineral soil surface. In their simulated burning experiment using artificially placed blackberry (*Rubus* spp.) and sumac (*Rhus copallina* and *R. glabra*) seeds, Cain and Shelton (2003) showed the potential variability among species. Sumac germination was enhanced 6- to 8-fold on burned plots relative to non-burn controls, whereas blackberry seed on the litter exhibited less than 1 percent viability following burning.

We still do not know the degree to which prescribed fires can offer selective control of certain species, or how the timing of the fire (dormant vs. growing season) will affect seed viability. Complete sterilization of the surface and upper layers of the soil may lead to significantly delayed recolonization following prescribed fires, which may result in serious problems with soil erosion, nutrient leaching, and loss of biodiversity. By contrast, improved germination conditions for nontarget species may serve to further exacerbate the already difficult process of regenerating oak in new forest stands.

The objectives of this study were to (1) compare the seed bank pre- and post-burn by examining the number of species and individual germinants within each species and (2) compare the fire temperature with the germination patterns established in the above objective.

SITE DESCRIPTIONS

Two sites (Falling Water and Meadows Knob) near Russellville, AR, that currently support mature oak stands suffering from severe decline were sampled. Preburn species composition for each site and burn treatment is described in Table 1. Both stands were fully stocked and did not have a recent history of harvesting, but some mortality of red oak species was noted. Basal areas for trees greater than 11.7 cm averaged 25.7 and 19.2 m^2 ha^{-1} for Falling Water and Meadows Knob, respectively.

Each site was scheduled to receive separate dormant-season and growing-season prescribed burns. Dormant-season prescribed burns were conducted in February 2007. Actual fuel loadings are unavailable. Air temperature, relative humidity, and wind speed averaged 24 °C, 39 percent, and 8 km hr^{-1}, respectively, at both sites. The growing season burns for each site were planned for early in the summer of 2007. Unfortunately, extremely wet weather prevented the application of the growing-season burn treatment.

MATERIALS AND METHODS

Seed Bank Sampling

The seed bank was sampled using eight to nine sample plots per burning treatment at each site. Two seed bank subsamples at each sample plot (north and south locations) were collected pre- and post-burn for the dormant-season prescribed burn in February 2007. Preburn samples for the growing-season prescribed burn treatments were collected in June in anticipation of the growing-season burn the following week. As mentioned above, the growing-season burns were not conducted due to prolonged rains during the early summer, and consequently the post-burn growing-season samples were not collected.

Sample locations for pre- and post-burn samples were identified prior to burning to avoid sampling bias. Additionally, pre- and post-burn subsample locations were placed no more than 1 m apart and located in such a way that fire impacts were not affected (i.e., subsamples were not arranged up and down the slope). Each seed bank subsample consisted of a 900-cm^2 area and included the litter layers and mineral soil to 5.0 cm in depth. Collected samples were stored on ice or refrigerated at 4 °C until germination testing began (<1 wk).

Germination Tests

The litter and soil from each subsample was mixed with approximately 100 g of heat-sterilized peat moss to improve the porosity and the water-holding capacity of the soil sample. The subsample-peat moss mixture was added to sterilized plastic germination trays (28 x 56 cm flats without holes) and transferred to a greenhouse for germination testing. Sixty-eight dormant-season and 32 growing-season samples (trays) were placed in a greenhouse for testing. Greenhouse conditions were maintained at 16 h of light and 8 h of darkness, and temperature was maintained at or near 21 °C for optimum germination conditions (Gross 1990). In some cases, maximum daily greenhouse temperatures rose to around 30 °C in the afternoon during exceptionally hot days (>38 °C). Germination tests were conducted for 60 days to quantify the "readily germinated" seed. For the dormant-season samples, a subsequent 60-day germination test was conducted following a 60-day stratification period at 4 °C to quantify the "dormant seed" pool. Time constraints prohibited the second stratification period for the growing-season samples.

Over each 60-day germination test, newly emerged germinants were assessed weekly. Once germinants developed sufficiently for identification, they were recorded and discarded to prevent any potential inhibition of other germinating seeds. Unknown individuals were carefully extracted from the sample, potted, and allowed to develop until flowering to aid in the identification process.

Fire Temperature

Fire temperature was recorded for the dormant-season burning treatments using circular aluminum tags painted with fire sensitive paints. The paints used had temperature sensitivities beginning at 93 °C, increasing at 14 °C intervals to 316 °C, from 343 to 427 °C increasing at 28 °C intervals, and ending at 482 °C. One set of painted tags per subsample location (for both pre- and post-burn samples) was suspended 30 cm above the forest floor on an aluminum wire frame and was no more than 3 m from each seed bank sample. Maximum fire temperature was recorded from the highest melting temperature of the paint on each wire rack.

Data Analysis

With the elimination of the growing-season burn treatment, no comparisons could be made between dormant and growing-season fires. The dormant-season burn was truly replicated on only two sites, which limited our ability to detect significant differences before and after burning. Instead, we elected to report descriptive statistics for each burning treatment and limited our comparisons to broader generalizations supported by the treatment trends. Calculations of the number of emergents were generated by expanding results from each 900 cm^2 subsample, not the area of the germination tray, to 1 m^2.

Additionally, regression analyses were employed to describe the relationship between maximum fire temperature and the number of individuals emerging from the seed bank. Significance testing was conducted at the alpha = 0.10 level.

RESULTS

Dormant-Season Sampling

Germination tests on the seed bank samples produced at least 30 different species or species groups between the two sites (Table 2). Species richness was greatest at the Falling Water site. Its preburn seed bank had 17 different species emerge during testing, while post-burn samples had 19 species. Seven species that were recorded in the pre-burn samples did not germinate following burning. However, nine additional species were tallied in the burned seed bank that were not present in the pre-burn samples (Table 2).

Similarly, the number of species from the Meadows Knob site that emerged during the study varied little between pre- and post-burn periods (10 and 11 species, respectively). But again, differences in species composition were sizable. Six species from the preburn seed bank were absent in post-burn germination tests. Likewise, seven species from the post-burn seed bank were absent from the preburn germination tests (Table 2).

While more diverse, Falling Water and Meadow Knob post-burn seed banks averaged 20 percent more emergents than the pre-burn seed bank. The total number of emergents following a dormant season burns averaged 38.2 compared to 31.8 emergents m^{-2} prior to burning (Table 2).

Growing-Season Sampling

Germination tests for the growing-season seed bank samples resulted in fewer numbers of species and emergents (Table 3) compared to the dormant-season collections (Table 2). Fifteen species were recorded from the growing-season collections. Again, the Falling Water site had the greater diversity in the soil seed bank (12 species), whereas the Meadows Knob site had eight species. Falling Water and Meadows Knob sites had eight and seven species that were present in the dormant-season pre-burn samples that were not recorded in the growing-season samples. Conversely, four and three species, respectively, were present in the growing-season samples that were not tallied in the dormant-season samples. The total number of emergents was low relative to the dormant-season seed bank. The initial 60-day germination tests resulted in 17.3 and 23.6 emergents m^{-2} for Falling Water and Meadows Knob sites, respectively (Table 2).

Table 2.—Pre- and post-burn emergence from the soil seed bank from two upland oak stands receiving dormant season prescribed burns

Species	Falling Water		Meadows Knob	
	Preburn	Post-burn	Preburn	Post-burn
	--------------------number of emergents m^{-2}--------------------			
Acer rubrum	2.8	2.8	2.4	0.0
Campsis radicans	0.5	0.0	0.0	0.0
Carya spp.	0.5	0.0	0.0	0.0
Desmodium sp.	0.0	1.9	0.8	0.0
Erechtites hieraciifolium	0.9	0.0	0.0	0.0
Graminoid (>4 species)	11.6	25.9	1.6	10.3
Lespedezia sp.	0.0	0.9	0.0	0.0
Nyssa sylvatica	0.0	0.9	0.0	0.0
Ostyra virginiana	0.5	0.0	0.0	0.0
Oxalis sp.	10.2	0.0	3.2	0.0
Physalis sp.	1.4	2.8	0.0	2.4
Phytolacca americana	0.9	1.9	0.8	1.6
Quercus alba	0.9	0.0	1.6	0.8
Quercus rubra	1.9	0.0	0.0	0.0
Rhus spp.	0.5	1.9	0.0	0.0
Sassafras albidum	0.0	0.9	0.0	0.0
Scutellaria ovata	6.0	4.6	1.6	2.4
Toxicodenron radicans	3.7	0.9	0.8	2.4
Vitis rotundafolia	0.0	1.9	6.3	0.0
unknown (7 species)	0.0	4.6	2.4	4.8
Total	42.1	51.9	21.4	24.6

Table 3.—Preburn emergence from the growing season soil seed bank in two upland oak stands in the Arkansas Ozark Highlands

Species	Falling Water	Meadows Knob
	------number of emergents m^{-2}--------	
Erechtites hieraciifolium	0.6	3.5
Graminoid (≥1793 species)	10.5	8.3
Nyssa sylvatica	0.6	0.0
Oxalis sp.	0.6	0.0
Phytolacca americana	1.2	4.2
Rhus spp.	0.6	3.5
Sassafras albidum	0.6	0.0
Scutellaria ovata	1.2	0.0
Vitis rotundafolia	0.0	0.7
unknown (4 speceis)	1.2	3.5
Total	17.3	23.6

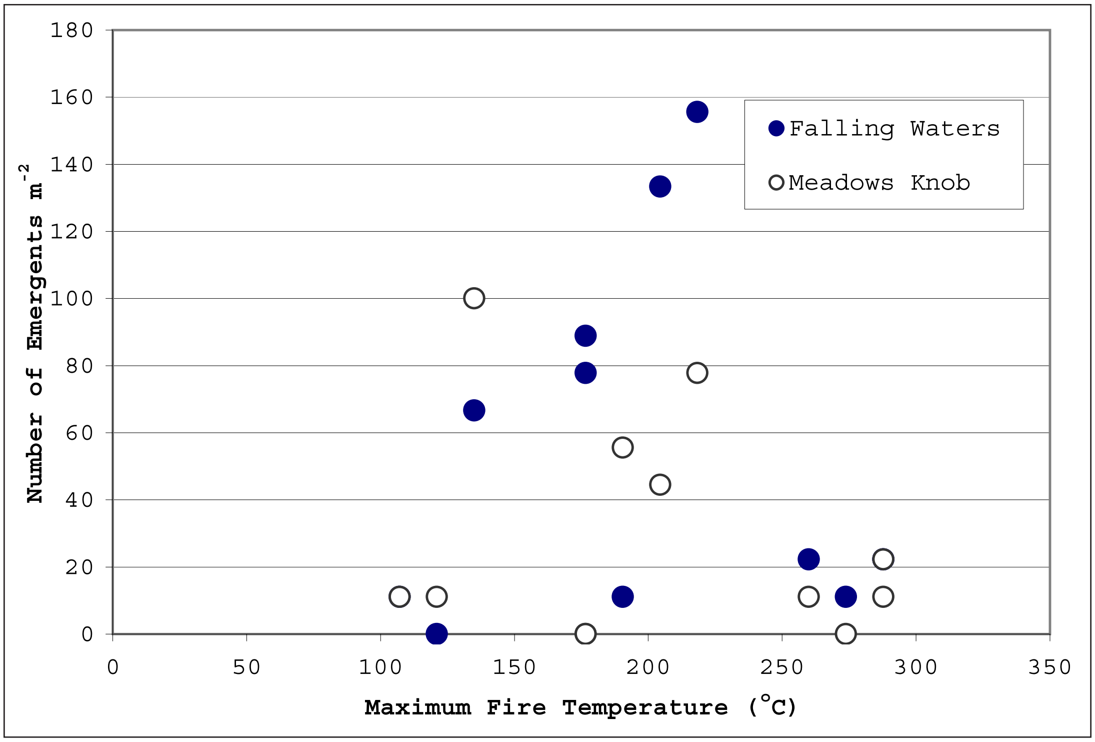

Figure 1. The effect of maximum fire temperature (30 cm above forest floor) from dormant season burns on the number of indivuduals emerging from the soil seed bank.

Fire Temperature

Average and median maximum fire temperatures for the dormant-season burns were 204 °C and 204 °C for Falling Waters and 279 °C and 239 °C for Meadows Knob, respectively. Maximum fire temperature had no apparent relationship with the number of individuals emerging from the seed bank (Fig. 1). The slope coefficient was nonsignificant (P>0.10). Also, the relationship between the number of emerged individuals and maximum fire temperature did not vary by site (P>0.10) (Fig. 1).

DISCUSSION

Unfortunately, early summer weather patterns for northern Arkansas prohibited USDA Forest Service staff from conducting the growing-season burn. This wet weather impaired our ability to compare the soil seed banks for each site relative to the two burning regimes (i.e., dormant vs. growing season). However, interesting patterns did emerge when we compared the pre- and post-burn seed banks on the dormant-season treatments.

The number of emergents that germinated from the seed bank was 11 and 23 percent greater in samples collected after burning for the Meadows Knob and Falling Waters sites, respectively (Table 2). This trend was consistent with past work demonstrating similar increases in prairie communities (Hulbert 1969). However, other studies show reduced emergence following fire (Cain and Shelton 1998, Blodgett and others 2000).

Fire temperatures recorded during the dormant-season burns are comparable to other hot prescribed fires (Glasgow and Matlack 2007b). Maximum fire temperature, as recorded here, was not a good predictor of emergence (Fig. 1). As noted in past research, fire duration and soil moisture may be supplementary factors needed for predicting damage from burning (Iverson and others 2006). Additionally, the soil is an excellent thermal insulator. Increased soil temperatures are often detectable for the upper few centimeters of the soil profile (Auld and Bradstock 1996), which would favor seeds buried deeper in the organic layers and mineral soil. However, the samples collected for this study were not stratified by depth, so we cannot determine if the viable seed that germinated was either resistant to fire or was buried deeper in the profile.

Apparently, burning treatments have the ability to alter the composition of the viable seed bank. Eight and nine species had fewer numbers of emergents compared to the pre-burn samples (Table 2) following the dormant-season burning treatment on the Meadows Knob and Falling Water sites. However, only two species had consistently fewer individuals for each site, namely *Q. alba* and one unknown species. By contrast, 9 and 16 species had higher numbers of individuals emerging from the seed banks following burning (Table 2). Here, six species or species groups had consistently greater emergence at both sites, namely at least three graminoid species, a *Physalis* spp., *Phytolacca americana*, and one unknown species. Several studies also confirm the increased germination of species like *Rhus* spp., *Phytolacca americana*, as well as many graminoid species (Cain and Shelton 2003, Glasgow and Matlack 2007a, Hulbert 1969).

The preburn dormant- and growing-season seed bank produced very similar numbers of emerged individuals, whereas the dormant-season seed bank from Falling Waters was twice that of the summer seed bank (Tables 2 and 3). The graminoids were the most prevalent taxa for the summer collections. This result may be a response to a longer stratification period on site or possibly due to differences in collection locations. Dormant- and growing-season samples were collected on slightly different locations within each study site, whereas preburn and post-burn samples were located at most 1 m apart.

Taxa that dominate forested seed bank samples are usually species with high fecundity, effective dispersal mechanisms, and the ability to remain dormant under unfavorable conditions (Glasgow and Matlack 2007a). This usually favors early successional species like the graminoids, *Phytolacca americana* and *Rhus* spp. The lack of viable seeds from the dominant tree vegetation was unexpected, but not surprising (Shiffman and Johnson 1992). The tree species that dominated the overstory at both sites (i.e., oaks) are characterized as having relatively low fecundity, limited dispersal, reduced or no dormancy, the capability to sprout, and some degree of shade tolerance. These characteristics would favor a somewhat periodic germination process and a long-term building of an advance reproduction pool. The tree species that germinated in this study were *Carya* spp., *Ostyra virginiana*, *Acer rubrum*, *Quercus rubra*, *Q. alba, Rhus* spp., *Nyssa sylvatica*, and *Sassafras albidum*. *Rhus* spp., *O. virginiana*, and *S. albidum* were the only species that were not found in the overstory that germinated in our seed bank samples, while *Pinus echinata*, *Q. velutina, Q. stellata*, and *Prunus serotina* were species that were present in the overstory but did not germinate from the seed bank.

The results of this study, although limited because one of the burn treatments from being implemented, still provides information concerning the composition of the soil seed bank of three mature upland oak sites in the Arkansas Ozark Highlands with and without prescribed fire.

The seed bank was composed almost entirely of nontree species. Most tree species found in mature upland stands do not have large persistent seed banks. This situation highlights the importance of the other sources of reproduction (sprouting and advance reproduction) when these stands are regenerated. Burning had little effect on the total numbers of germinated seed. However, there does appear to be shifts in species composition, generally favoring graminoid species.

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FIRE SCARS AND TREE VIGOR FOLLOWING PRESCRIBED FIRES IN MISSOURI OZARK UPLAND FORESTS

Aaron P. Stevenson, Rose-Marie Muzika, and Richard P. Guyette[1]

Abstract.—The goal of our project was to examine basal fire scars caused by prescribed fires and tree vigor in upland forests of the Missouri Ozarks. Fire scar data were collected in 100 plots from black oak (*Quercus velutina* Lam.), scarlet oak (*Q. coccinea* Muench.), Shumard oak (*Q. shumardii* Buckl.), post oak (*Q. stellata* Wangenh.), white oak (*Q. alba* L.), hickories (*Carya* spp. Nutt.), and shortleaf pine (*Pinus echinata* Mill.). Crown dimensions were measured in 99 plots for scarlet oak and black oak, and crown dimensions were converted to crown and tree vigor index values. Fire scar data for scarlet oak and Shumard oak were grouped into a red oak species group because of similar bark characteristics (i.e., fire tolerance) between the two species and a small sample size for Shumard oak. Results indicate large fire scars and more frequent scarring on southwest-facing slopes for individual species groups. For all species groups, scar frequency and scar height were positively correlated with stem-bark char height, a proxy for fire intensity. Red oaks were the most sensitive species group to scarring, and shortleaf pine and post oak were the most fire-resistant. Tree vigor index values indicated that black oak vigor was lower in unburned plots and crown vigor index indicated that scarlet oak vigor was lower in burned plots. The relationship between fire intensity, aspect, and species composition are important factors to consider when using prescribed fire.

INTRODUCTION

Prescribed fire is an effective tool to achieve specific ecosystem goals (Vose 2000). In Missouri, public agencies are using prescribed fire to restore glade, savanna, and woodland communities and to reduce hazardous fuel loads. A consequence of using prescribed fire is the potential to damage timber resources caused by heat-related cambial injury and subsequent scarring. High-intensity prescribed fires may also cause scorch in overstory hardwoods, thereby negatively affecting crown health (Brose and Van Lear 1999).

Many studies have used stem-bark char height as a postfire predictor of tree mortality in conifers (Dixon and others 1984, Regelbrugge and Conrad 1993, Menges and Deyrup 2001, Beverly and Martell 2003, Keyser and others 2006) and eastern hardwoods (Loomis 1973, Regelbrugge and Smith 1994). Low-intensity prescribed fires in eastern oak-dominated forests do not cause high rates of overstory mortality but can injure trees and cause subsequent basal scarring (Wendel and Smith 1986, Franklin and others 2003). Fire-caused scars in central hardwoods are a serious problem when managing timber resources, in part because of subsequent invasion by insects and fungal pathogens and the loss of timber volume (Berry and Beaton 1972, Loomis 1973). Postfire injury models have used bole blackening and stem-bark char height as important predictors of basal injuries in hardwoods (Loomis 1973, Simard and others 1986). Jenkins and others (1997) used landscape variables to predict fire scar frequency following a wildfire in northern Arkansas.

Evidence of fire impacts on crown conditions is most apparent in conifer-dominated stands, where intense crown damage leads to reduced diameter growth or high mortality rates (Peterson and Arbaugh 1986, Henning and Dickmann 1996, Stephens and Finney 2002, Kobziar and others 2006). Little research

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exists on the effects of fire on crown conditions in oak-hickory forests. Brose and Van Lear (1999) studied prescribed fire in an oak-dominated shelterwood and found spring and summer fires decreased the proportion of oaks with healthy crowns. They also reported that fire damage to other hardwoods manifested as declining crown conditions. Tree crown conditions have recently been used as indicators of forest health (U.S. Department of Agriculture 2005, Zarnoch and others 2004) and individual tree health (Starkey and Guldin 2004), and examining crown conditions in oak-dominated stands managed with prescribed fire can provide insight into fire impacts on forest health.

STUDY AREA

The study sites are located in upland forests across the Missouri Ozark Highlands. Data were collected from public and private lands across three ecological subsections (ES): the Current River Hills ES, the White River Hills ES, and the Meramec River Hills ES (Nigh and Schroeder 2002). Study sites include: Caney Mountain Conservation Area in the White River Hills ES; Pea Ridge Conservation Area in the Meramec River Hills ES; and Peck Ranch Conservation Area, Clearwater Lake Conservation Area, Logan Creek Conservation Area, Mule Mountain in Rocky Creek Conservation Area, Ozark National Scenic Riverways, and The Nature Conservancy's Chilton Creek Management Area in the Current River Hills ES.

The Ozark Highlands is characterized as hilly to rugged lands with relatively thin, rocky soils. The pre-EuroAmerican settlement vegetation in the uplands was a mosaic of mixed-oak and pine-oak woodlands and forests (Batek and others 1999). The current upland forests are dominated by white oak (*Quercus alba* L.), scarlet oak (*Q. coccinea* Muench.), and black oak (*Q. velutina* Lam.), with minor representations from hickories (*Carya* spp. Nutt.) and shortleaf pine (*Pinus echinata* Mill.). The range of scarlet oak does not extend into the White River Hills study area, but Shumard oak (*Q. shumardii* Buckl.) was relatively common throughout the area. Current management objectives in the study area include using prescribed fire to restore oak and pine-oak woodlands, including reducing woody undergrowth, stimulating native grasses and forbs, and reducing litter depths (Nelson 2005).

METHODS

Within each study area, burn units were selected for sampling. A burn unit is defined as an area surrounded by firebreaks and managed with prescribed fire. Twenty-two burn units were sampled from three ecological subsections: one unit in the Meramec River Hills, three units in the White River Hills, and 18 units in the Current River Hills. Each burn unit can be characterized as an upland oak- or pine-oak dominated forest matrix with glade inclusions and woodland intergrades. Burn units ranged in area from 10 ha to 660 ha. Each burn unit had at least one dormant season prescribed fire in the last 5 years. In each burn unit, transects were established along the slope of the hill in forested areas with an oak-dominated overstory. The number of transects per burn unit varied according to the size of the burn unit.

Sampling occurred in 20-m radius plots located along each transect. Transects were stratified by slope position (upper slope, middle slope, lower slope). Plots were systematically located within each slope position and were at least 40 m from forest edge and no less than 75 m from other plots. If a plot location did not contain at least 15 oaks greater than 10 cm diameter at breast height (d.b.h.), then the plot was relocated to the closest point that met this requirement. Plots per transect ranged from two (no middle slope position sampled) to three (all three slope positions sampled) based on the length of the hill. A total of 100 plots were sampled across the study area. Plots were equally sampled on northeast- (316°-135°) and southwest-facing (136°-315°) slopes. Glades, woodlands, and forests with high levels of fire-caused overstory mortality were not sampled.

The aspect of each plot was recorded by measuring the direction of the slope at plot center. A plot-level mean stem-bark char height was determined for each plot. Bark char refers to any blackening of stem bark due to fire. Field observations noted that shortleaf pine bark char was consistently higher than bark char on hardwoods, and therefore shortleaf pine bark char was not included in the plot-level calculation. Plots were subdivided into one-third subplots and a mean maximum bark char height on hardwoods was calculated from at least two char measurements in each one-third subplot.

For trees greater than 10 cm d.b.h., the three largest fire scars were measured for white oak, scarlet oak, Shumard oak, black oak, post oak (*Q. stellata* Wangenh.), hickories, and shortleaf pine. We included fire scar data for scarlet oak and Shumard oak in a red oak species group because the species have similar bark characteristics (i.e. fire tolerance) and we had only a small sample size for Shumard oak. Scar measurements included scar height and width at scar midpoint. The frequency of scarring per plot was recorded for all trees greater than 10 cm d.b.h. for the same six species groups.

Tree height (H), crown radius (CR), live crown ratio (LCR), crown density (CD), and d.b.h. were recorded for up to four randomly selected black oak and scarlet oak overstory trees in plots occurring in the Current River Hills. Crown density is defined as the amount of crown branches, foliage and reproductive structures that block light through the crown (Zarnoch and others 2004). Crown density was estimated by ocular assessment using a crown density-foliage transparency card from the 3.0 phase 3 field guide—crown: measurements and sampling (USDA Forest Service 2005). Black oak was also sampled from plots in the White River Hills.

For a direct comparison of tree vigor in unburned and burned areas, five stands not managed with fire were sampled. Stands were selected based on two criteria: 1) similar physiognomy (i.e., overstory species composition, stand structure) as burned areas; and 2) close proximity to burned areas. Transects and plots were established in unburned areas in the same manner as in burned areas. In each plot crown measurements were recorded for overstory black oaks and scarlet oaks. A total of 68 burn plots and 31 unburned plots were inventoried for sample tree measurements.

Crown surface area (CSA) for each individual sample tree was calculated based on the assumption that the crown surface is approximated by a parabaloid (Zarnoch 2004). Stem surface area (SSA) was calculated by assuming the bole of the tree was equal to the surface area of a cone using tree height (m), d.b.h. (cm), and an adjustment coefficient (Whittaker and Woodwell 1967). Two measures of tree vigor, crown surface index (CSI) and tree vigor index (TVI), were calculated using CSA and SSA (Voelker 2004):

Eq. 1. $SSA = ((\pi \times d.b.h. \times H) / 2) \times c$

Eq. 2. $CSI = CSA \times (1 - LCR)$

Eq. 3. $TVI = CSI / SSA$

where c = 1.268, an adjustment coefficient for scarlet oak from Whittaker and Woodwell (1967). Calculations for this study assume the adjustment coefficient for scarlet oak is the same for black oak (Voelker 2004).

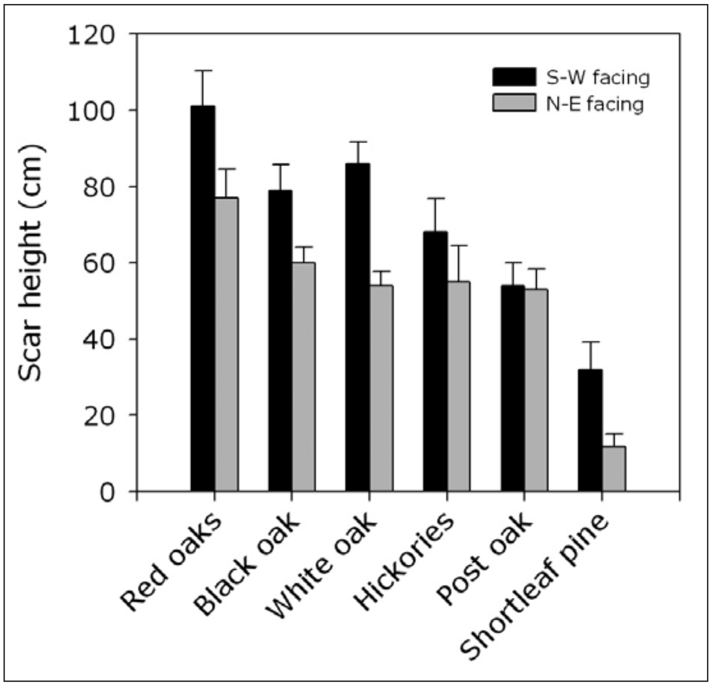

Figure 1.—Mean maximum scar height on southwest- and northeast-facing slopes for six tree species groups.

Analysis

Plot-level mean maximum scar height was determined for each species group. Scar frequencies at each plot were converted to a percentage of trees scarred for each species and for all selected species groups combined. Mean scar height and percent trees scarred were determined for each species on northeast and southwest-facing slopes.

Scar heights were normalized by calculating the natural logarithm of the mean. Scar percentages were normalized using Bartlett's arcsine transformation (Zar 1999). Aspect was transformed to a linear scale following Beers and others (1966). Multiple regression analysis was used to model scar height and scar percentage with respect to bark char height and aspect. For each model, char height was added and retained if its p-value was less than $\alpha = 0.05$. Aspect was then added to the model and retained if its p-value was less than $\alpha = 0.05$. The small sample size precluded regression analysis for shortleaf pine.

Mean CSI and TVI were determined for black oak and scarlet oak at each plot where overstory sample trees were measured. The effect of burning on CSI and TVI was tested for both black and scarlet oak using a mixed-model analysis of variance ($\alpha = 0.05$), where treatment (burned or unburned) is the fixed effect and unit (unburned stand or burn unit) is the random effect.

RESULTS

Mean scar height for each species group was higher on exposed versus protected slopes (Fig. 1). Overall, red oaks had the greatest scar heights and shortleaf pine had the lowest scar heights on both northeast-facing and southwest-facing slopes. Percent of trees scarred was highest for each species and all species groups combined on exposed slopes (Fig. 2). Red oaks and black oak had the highest percentage of trees scarred on exposed slopes, and shortleaf pine had the lowest scar percentage on exposed and protected slopes.

Multiple regression analysis revealed that bark char height was a weak to moderate predictor of mean scar height for all six species groups. Predictions from the model indicated red oaks to be the most sensitive

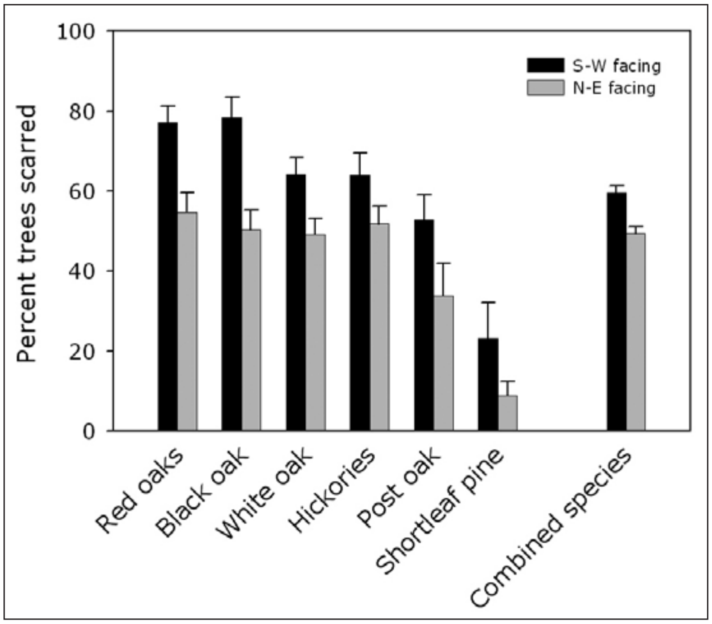

Figure 2.—Percent of trees scarred on southwest- and northeast-facing slopes for six species groups and combined species.

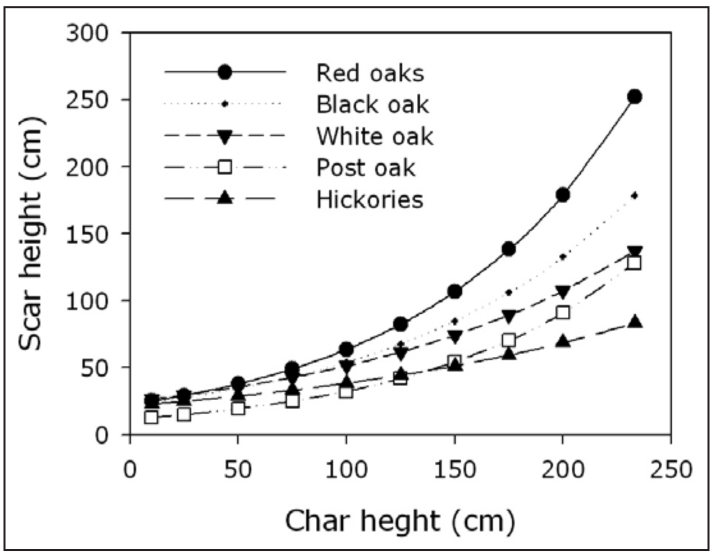

Figure 3.—Predicted scar height for five species groups based on stem-bark char height on hardwoods.

to scarring, followed by black oak and white oak, and post oak and hickories (Fig. 3). Aspect was a weak predictor of scar height for white oak and post oak (Table 1). For percentage trees scarred, stem-bark char height was a weak to moderate predictor for each species. Aspect was a weak predictor of percent trees scarred for red oaks, white oak, and all species groups combined (Table 2).

For overstory sample trees, mean d.b.h. and tree heights (H) were higher in unburned sites for scarlet and black oak (Table 3). CSA and CR were higher in unburned plots for scarlet oak, but black oak showed little differences in CSA and CR between burned and unburned plots. There was no difference in the CSI of black oak in burned and unburned plots, but scarlet oak had a lower CSI in burned plots ($F_{1,18} = 5.58$, $p < 0.03$) (Table 3). There was no difference for the tree vigor index (TVI) of scarlet oak, but TVI of black oak was lower in unburned areas ($F_{1,27} = 5.82$, $p < 0.04$)(Table 3).

Table 1.—Summary of multiple regression analysis for mean maximum scar heights of five Missouri tree species groups

Species	No. plots	Predictors	R^2	p-value
Red oaks[1]	82	char[2]	0.46	<0.001
Black oak	69	char	0.41	<0.001
White oak	93	char, aspect[3]	0.32	<0.001
Post oak	40	char, aspect	0.44	<0.001
Hickories	67	char	0.18	<0.001

[1]Red oaks include scarlet oak and Shumard oak
[2]Char = mean maximum bark char height (m) within a plot
[3]Aspect = transformed aspect (Beers and others 1966)

Table 2.—Summary of multiple regression analysis for percentage of trees scarred for five tree species groups and combined species

Species	No. plots	Predictors	R^2	p-value
Red oaks[1]	88	char[2], aspect[3]	0.37	<.001
Black oak	79	char	0.25	<.001
White oak	97	char, aspect	0.32	<.001
Post oak	57	char	0.30	<.001
Hickories	73	char	0.16	<.001
Combined species	100	char, aspect	0.30	<.001

[1]Red oaks include scarlet oak and Shumard oak
[2]Char = mean maximum bark char height (m) within a plot
[3]Aspect = transformed aspect (Beers and others 1966)

Table 3.—Mean and standard error (in parentheses) for variables measured for overstory scarlet oak and black oak. Different letters represent within-species differences between CSI and TVI in burned and unburned areas.

	Scarlet oak		Black oak	
	Burned	Unburned	Burned	Unburned
d.b.h. (cm)	33.0 (7.6)	38.6 (9.9)	33.6 (8.1)	36.4 (8.1)
H (m)	20.2 (3.2)	24.9 (3.3)	20.2 (2.8)	22.0 (3.0)
CR (m)	4.0 (0.9)	4.4 (1.3)	3.6 (0.9)	3.4 (0.8)
CSA (m^2)	68.0 (33.2)	86.4 (37.7)	55.3 (22.2)	52.5 (21.6)
CSI[a]	66.3 A (5.3)	94.3 B (10.6)	57.3 (4.4)	55.1 (2.9)
TVI[a]	4.5 (0.2)	4.6 (0.1)	3.5 A (0.2)	3.9 B (0.1)

H = total tree height; CR = average crown radius; CSA = crown surface area; CSI = crown surface index; TVI = tree vigor index.
[a]Values derived from measured variables

DISCUSSION

Based on the scar height and percent trees scarred results, species could be ranked according to sensitivity to scarring:

red oaks > black oak = white oak > post oak = hickories > shortleaf pine

These results are similar to other studies examining fire damage in hardwoods. Harmon (1984) found tree survival from a low-intensity surface fire increased with increasing bark thickness, and ranking fire sensitivity based on his bark thickness findings revealed scarlet oak as the most fire-sensitive and shortleaf pine as the least fire-sensitive of the species we examined. Regelbrugge and Smith (1994) found scarlet oak was the least fire-resistant of the oaks they examined. Studies in the Missouri Ozarks found scarlet oak as the most sensitive species to scarring, followed by white oak, black oak, hickories, and post oak (Burns 1955, Paulsell 1957).

Stem-bark char height has long been used to predict postfire mortality, but few studies have used it to predict fire injuries. Only two studies were found that used stem-bark char as an important predictor of fire injuries. Stem-bark char was used to predict scar height and scar width in Missouri oaks and hickories (Loomis 1973) and to predict percent circumference killed in northern hardwoods (Simard and others 1986). Our findings concluded that stem-bark char is an effective postfire variable for assessing scar heights and percent trees scarred in Missouri oaks and hickories.

Aspect determines solar radiation exposure on a slope, which in turn affects air temperature and fuel moisture levels. These factors contribute to fire intensity, and thus fire temperatures are higher on more exposed southwest and southeast slopes than on protected northeast facing slopes (Schwemlein and Williams 2006). Although char height is an approximate indicator of fire intensity, our results support the findings of Jenkins and others (1997) that aspect needs to be included in postfire injury models to capture a more complete effect of fire intensity.

Black oak is considered a relatively fire-tolerant species due to its relatively thick bark (Harmon 1984). Thicker bark can insulate the cambium from fire-caused injury and prevent injury-related crown dieback. The CSI for black oak was not different between burned and unburned areas, but the higher TVI in burned areas reflects the capacity for black oaks in prescribed fire stands to support a crown with less stem surface area than black oaks in unburned stands. It is possible that black oaks are able to better compete with other species for crown space in burned areas.

The lower CSI of scarlet oak in burned areas supports other research showing that fire decreased the proportion of oaks with healthy crowns (Brose and Van Lear 1999). Scarlet oaks are the most fire-sensitive oak species in Missouri and we expected them to have reduced crown vigor in burned stands. Overall TVI of scarlet oak was not different in burned and unburned areas. The lack of difference could be explained by the metric used to express tree vigor, which relied on weighting the CSI by the SSA, and scarlet oaks in unburned areas had a higher mean SSA due to larger mean diameters and tree heights.

It is unclear why scarlet oak and black oak had higher mean diameters and heights in unburned areas. Although the basal area in burned (21.5 ± 6.1 m^2 per ha) and unburned areas (21.4 ± 5.3 m^2 per ha) is nearly identical, it is possible that the unburned areas we selected for study sites were of higher site quality and higher productivity than burned areas targeted for woodland restoration and prescribed fire management. Although care was taken to ensure unburned areas sampled had similar forest structure and composition as burned areas sampled, it is possible that differences in environmental conditions between burned and unburned areas led to spurious results.

Based on these findings, resource managers using prescribed fire may improve the likelihood of satisfying the management objectives by realizing the consequences of prescribed burning. Postfire impacts such as scarring are dependent not only on fire intensity, but also on species composition and aspect. After a relatively intense fire, stands dominated by scarlet oak or Shumard oak will have more large fire scars than stands dominated by shortleaf pine and post oak. Under normal fire conditions, trees on southwest-facing slopes will be at higher risk for scarring than trees on northeast-facing slopes. Managers using prescribed fire must take into account the relationship between fire intensity, aspect, and species composition.

ACKNOWLEDGMENTS

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STATUS OF OAK SEEDLINGS AND SAPLINGS IN THE NORTHERN UNITED STATES: IMPLICATIONS FOR SUSTAINABILITY OF OAK FORESTS

Chris W. Woodall, Randall S. Morin, Jim R. Steinman, and Charles H. Perry[1]

Abstract.—Oak species are a substantial component of forest ecosystems in a 24-state region spanning the northern U.S. During recent decades, it has been documented that the health of oak forests has been experiencing large-scale decline. To further evaluate the sustainability of oak forests in nearly half the states of the U.S., the current status of oak seedlings and saplings was analyzed using a variety of large-scale data sources, such as forest inventories and climate summaries. Study results indicated that oak seedlings and saplings tremendously lag other oak forest components (e.g., large trees) in terms of their stand occupancy relative to non-oak tree species. An indicator of future oak sustainability was developed and correlated with climatic variables indicating that climatic stresses may be an additional contributing factor to regional oak sustainability. Overall, the future of oak forests in the northern U.S. is at risk unless disturbances occur that increase oak regeneration and reduce oak mortality, especially among seedlings/saplings.

INTRODUCTION

It has been proposed that North America's oak forests may be entering an extended period of poor health (Kessler 1992), a situation that has been occurring at a national scale for the past century (Thomas and Boza 1984). The deterioration of oak forest health, evidenced by numerous symptoms and precipitated by various causal factors, is collectively termed "oak decline" (Thomas and Boza 1984, Starkey and Oak 1989, Lawrence and others 2002). Oak decline results from the interaction of predisposing (e.g., low site productivity, advance tree ages), inciting (e.g., insect defoliation, droughts), and contributing factors (e.g., poor forest management practices) (Starkey and Oak 1989, Manion, 1991, Lawrence and others 2002). This multitude of stresses eventually weakens oak trees, resulting in sparse foliage, thin crowns, crown dieback, reduced radial growth, and eventually death (Lawrence and others 2002). Silvicultural efforts to reduce tree mortality have included stand density reductions, increasing species diversity, and removal of senescing oaks (Clatterbuck and Kauffman 2006). Because oak decline is a phenomenon with a complex etiology (Manion 1991, Oak and others 1996), there is need for baseline data, long-term studies, and new analytical procedures (Kessler 1989, Nebeker and others 1992, Oak and others 1996).

The decline and mortality of oaks have been noted across large scales since the late 1970s. Researchers often consider oak decline in conjuction with the broader issue of oak sustainability (for examples, see Dwyer and others 1995, Lawrence and others 2002, Moser and others 2006, Shifley and Woodall 2007, Widmann and Williams 2007, Woodall and others 2005a). These studies observe that by volume, oak forests currently dominate many northern forests. Across the northern United States, the growing stock volume of oak tree species on timberland has increased more than 77 percent since 1963 to a present-day

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total of greater than 1.4 billion cubic meters (Smith and others 2004, In press). During the same period, however, volumes of other tree species commonly associated with oak forest types, have risen at even more dramatic rates. Ash (*Fraxinus* spp.), maple (*Acer* spp.), and yellow-poplar (*Liriodendron tulipifera*) had their net growing stock volumes increase by 251, 134, and 132 percent since 1963, respectively. Current total volume of ash, maple, and yellow-poplar are approximately 1.4, 0.4, and 0.3 billion cubic meters, respectively. Despite oak's prevalence in terms of volume across the northern U.S., evidence from recent studies (Moser and others 2006, Shifley and Woodall 2007, Widmann and Williams, 2007) suggests that both oak sapling mortality and a lack of seedlings portend a doubtful future for oak forests. Given that oak seedlings and saplings may indicate the sustainability of future oak resources, their further examination is warranted.

The goal of this study was to conduct an assessment of oak seedlings and saplings as an indicator of oak forest sustainability in the 24-state region of the northern United States. Specific objectives were: 1) to determine the current status (e.g., trees per ha and mortality) of oak seedlings/saplings in contrast to non-oak species seedlings/saplings; 2) to suggest an indicator of oak sustainability building upon results from the previous objective; and 3) to correlate the indicator of oak sustainability with both stand-level parameters, such as oak mortality, and climatic factors, such as average annual precipitation.

METHODS

Forest Inventory Data

The Forest Inventory and Analysis (FIA) program of the USDA Forest Service, the only congressionally mandated national inventory of U.S. forests, conducts a 3-phase inventory of forest attributes of the country (Bechtold and Patterson 2005). The FIA sampling design is based on a tessellation of the United States into hexagons approximately 2,428 ha in size with at least one permanent plot established in each hexagon. In phase 1, the population of interest is stratified and plots are assigned to strata to increase the precision of estimates. In phase 2, tree and site attributes are measured for forested plots established in each hexagon. Phase 2 plots consist of four 7.32-m fixed-radius subplots on which standing trees are inventoried. For assessment of current oak forest attributes, inventory data from 1999 onwards were utilized; 17,421 inventory plots were included in the analysis. This study's 24-state study region includes: Connecticut, Delaware, Illinois, Indiana, Iowa, Kansas, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Nebraska, New Hampshire, New Jersey, New York, North Dakota, Ohio, Pennsylvania, Rhode Island, South Dakota, Vermont, West Virginia, and Wisconsin (Fig. 1). Plots were included in the analysis if at least one oak tree greater than 2.54 cm diameter at breast height (d.b.h.) was measured. Because growth/removals/mortality were not observed on all inventory plots, lower sample sizes occurred when these variables were utilized and are noted in results.

Climate Data

Three climatic variables were used in this study: average annual maximum temperature (TMAX), average annual minimum temperature (TMIN), and average annual precipitation (PRECIP). Data for these variables were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset utilizing a 4-km grid cell size (PRISM Group 2004). Each of these three variables is represented by a 30-year climate normal. As such, PRECIP is the mean annual total precipitation from 1971 to 2000. TMAX and TMIN are the mean daily temperature extremes for that period.

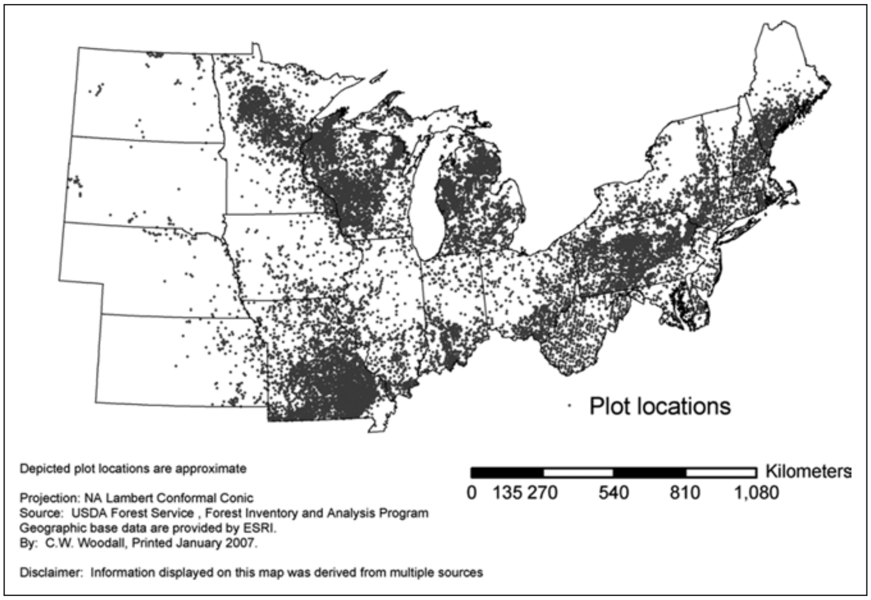

Figure 1.—Distribution of study plots with at least one oak tree present (d.b.h > 2.54 cm) (Note: plot locations are approximate due to privacy laws)

Analysis

For the purposes of this study, seedlings were defined as live trees with a d.b.h. less than 2.54 cm and at least 30.48 cm in height. Saplings were defined as live trees with a d.b.h. less than 15 cm. All study plots were assigned to classes according to ratios of oak biomass to total stand biomass. These classes represented a continuum of oak prevalence in forest stands. Next, the mean ratios of oak species attributes to non-oak species attributes were determined by each class of oak biomass ratio. Examined oak species attributes were: 1) trees per hectare (TPH) with a d.b.h >15 cm; 2) trees per hectare with a d.b.h. <15 cm; 3) average annual growth (gross); 4) average annual removals; 5) average annual mortality; 6) seedlings per hectare; 7) average annual growth (gross) for trees with a d.b.h. <15 cm; 8) average annual removals for trees with a d.b.h. <15 cm; and 9) average annual mortality for trees with a d.b.h. <15 cm).

Based on the initial results of the preceding analyses, an indicator of oak sustainability was developed that incorporates attributes of tree seedlings and saplings:

$$Indicator = Seed_R + Sap_R - SapMort_R \qquad [1]$$

Where $Seed_R$ is the ratio of oak seedlings to non-oak seedlings per plot, Sap_R is the ratio of oak saplings to non-oak saplings per plot, and $SapMort_R$ is the ratio of oak sapling mortality to non-oak sapling mortality per plot.

When we use the formulation as an indicator of oak forest sustainability, the highest value of 2 indicates that all seedlings and saplings in an oak forest were oak species with no mortality of oak saplings. A value of 0 indicates either that no oak species constituted seedlings/saplings or sapling mortality outweighed seedlings/saplings. Finally, the indicator was then correlated (Pearson's correlation coefficients) with ancillary data including climatic variables and stand variables not included in the indicator formulation.

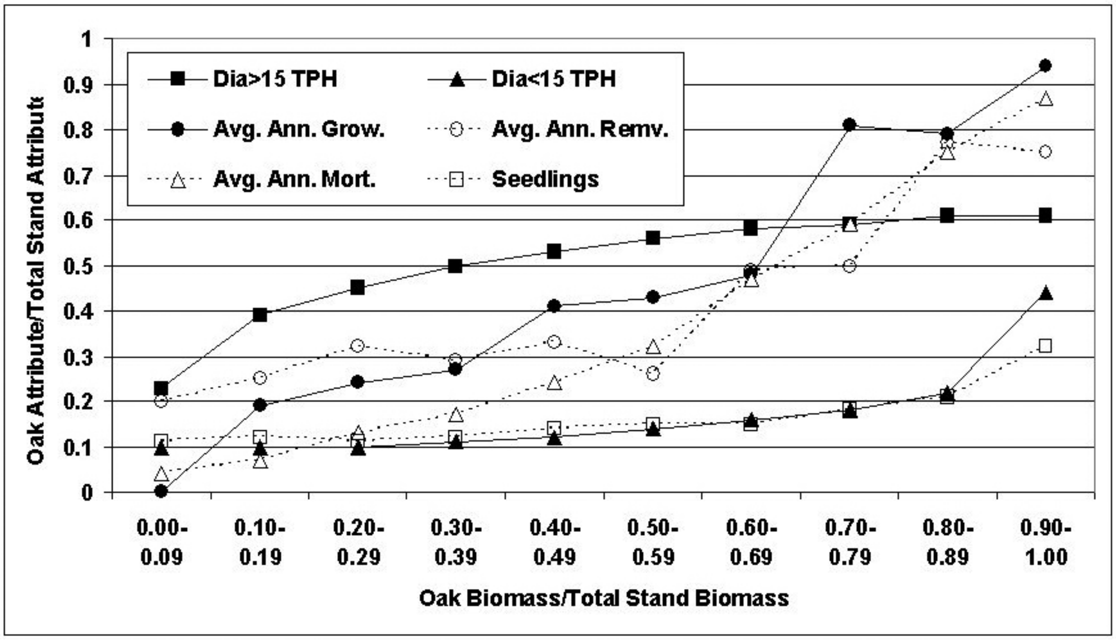

Figure 2.—Mean ratios of oak forest attributes by classes of oak biomass ratio (ratio of oak species biomass to non-oak biomass) for all inventory plots containing at least one oak tree.

RESULTS

Status of Oak Seedling and Saplings

Study results indicate that the average annual growth, mortality, and removals of oak tree species are commensurate with the amount of total stand biomass occupied by oak species (Fig. 2). For example, in a stand that had between 80 and 90 percent of its biomass in oak species, oak species themselves constituted between 75 and 80 percent of the stand's average annual growth, removals, and mortality. In contrast, seedlings/saplings accounted for only roughly 21 percent of the total seedlings/saplings in the same stand. Even in stands with more than 90 percent of their tree biomass in oak species, seedlings/saplings represented only a minority of the tree species in the stand. The very low amount of seedlings/saplings was common across all oak biomass ratio classes. As found in this and earlier studies (Woodall and others 2005b, Moser et al. 2006, Shifley and Woodall 2007, Widmann and Williams 2007), the oak resource across large scales is typified by mature oak forests that constitute a sizable portion of forest volume growth but have very few seedlings and/or sapling-sized trees to maintain oak forest types in the future.

The mean ratios of oak sapling average annual growth, removals, and mortality to those of non-oak species by classes of oak biomass ratios indicated that oak trees have less average annual growth compared to non-oak saplings in oak forests (Fig. 3). The mortality and removals of oak saplings was roughly commensurate with what may be expected in oak forests. For example, in a stand that had between 80 and 90 percent of its biomass in oak species, oak species themselves constituted between 55 and 65 percent of the stands' average annual removals and mortality but only 41 percent of the average annual growth. Even in stands with more than 90 percent of their biomass in oak trees, oak sapling growth was only 61 percent of all the sapling growth in the stand. Overall, oak saplings are conspicuously absent in large numbers in forest stands dominated by oak biomass. Although oak sapling mortality is not excessively high, oak sapling growth is poor relative to non-oak species, indicating a higher hazard of future mortality.

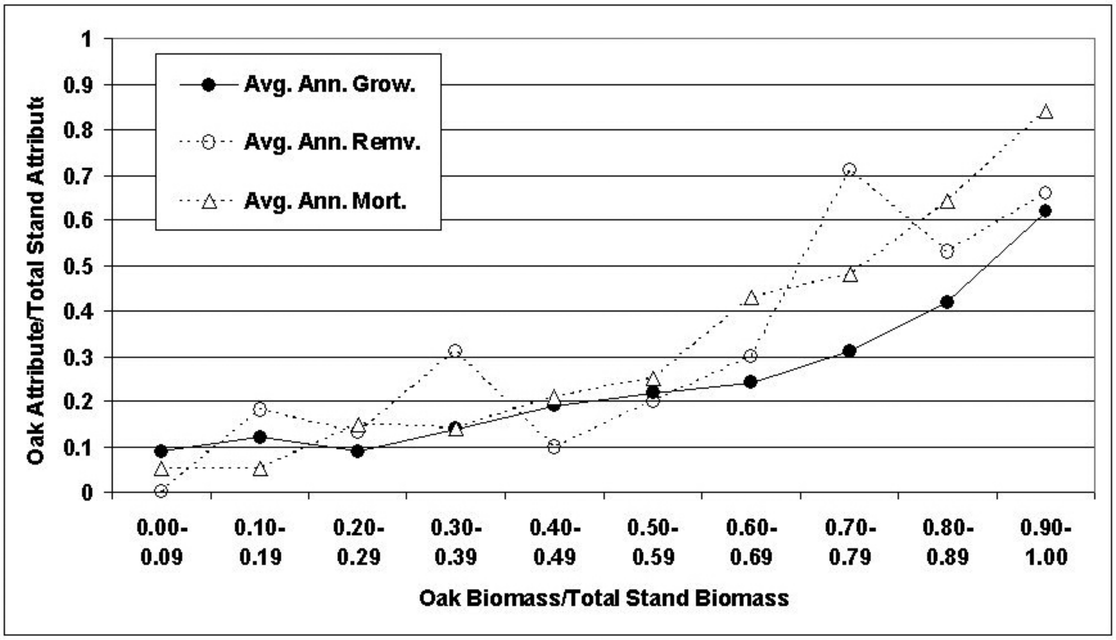

Figure 3.—Mean ratios of oak sapling attributes (d.b.h. <15 cm) by classes of oak biomass ratio (ratio of oak species biomass to non-oak biomass) for all inventory plots containing at least one oak tree.

A Proposed Indicator of Oak Sustainability

The proposed oak sustainability indicator simply incorporates the status of oak seedlings and saplings relative to non-oak species into one indicator. The order statistics of the oak sustainability indicator displayed a stark and dismal assessment of the future of oak forests in the northern states (Table 1). The median oak forest in the multi-state region had seedlings and saplings (minus average annual sapling mortality) that constituted only 20 percent of the stand's total seedling/saplings counts (minus sapling mortality). The distribution of this study's oak sustainability indicator was heavily skewed to the left where the mode was 0 and the first quartile was only 0.02. Unless oak species are a superior survivor of smaller-tree mortality compared to other non-oak tree species, the extent and condition of current oak forests will likely decline in the future. In numerous species mixtures, oak species definitely out-compete non-oak seedlings to perpetuate oak forests (Johnson and others 2002). The critical question is whether the disparity between oak and non-oak seedlings can be ameliorated by oak's superior survival traits. Therefore, monitoring the survival of oak regeneration relative to non-oak species may be critical to the forecasting of the nation's oak resources.

Table 1.—Order statistics for this study's oak sustainability indicator for oak forest types in the northern U.S. (n=5,729) (Note: mean=0.39, mode=0.00)

Percentiles	Oak Sustainability Indicator
100 Maximum	2.00
99	1.89
95	1.40
90	1.09
75 Quartile 3	0.60
50 Median	0.20
25 Quartile 1	0.02
10	0.00
5	0.00
1	0.00
0 Minimum	0.00

Oak Sustainability Indicator and Ancillary Information

We correlated the oak sustainability indicator with other oak forest attributes (e.g., average annual oak growth) and climatic variables (e.g., TMAX) (Table 2). The variables showed only weak correlations ; some correlation coefficients were near 0 (p-value > 0.05). The oak sustainability indicator was negatively

Table 2.—Pearson's correlation coefficients and significance for this study's oak decline indicator, additional oak forest attributes, and ancillary information in oak forest types, North Central and Northeastern U.S.

	Oak sustainability indicator		
Variables	Corr. Coeff.	p-value	n
Mean annual max. temp.	-0.20	<0.001	1732
Mean annual min. temp.	-0.01	0.605	1732
Mean annual precipitation	-0.16	<0.001	1732
Mean annual oak growth	0.02	0.413	1543
Mean annual oak mortality	0.01	0.605	1543
Oak trees per hectare (d.b.h >15 cm)	0.22	<0.001	5729

correlated with all climatic variables and achieved its highest correlation (-0.20) with TMAX. These results lend further credence to the hypothesis that higher temperatures and the sometimes associated periods of drought may be leading to the decrease in oaks (for examples see Starkey and others, 1989, Moser and others 2005, Clatterbuck and Kaufmann 2006), in particular the rate of establishment and survival of oak seedlings/saplings. On the other hand, the negative correlation (-0.16) of the oak sustainability index with precipitation is a surprising result; it may be more reflective of the coarse spatial and temporal scale of the climatic data rather than of site-specific response to one summer's drought.

CONCLUSIONS

This study highlights the continued progression of oak decline in forests of the northern U.S. This decline, although first evidenced by the mortality of large red oaks, may actually be better foretold by the current status of oak seedlings and saplings across large-regions. The inclusion of oak regenerative capacities in regional oak resource assessments may serve as an indicator of the negative impacts of possible climate change and large-sized oak mortality (e.g., reduced oak seed banks). Future oak sustainability explorations should include more explicit spatial analyses, refined assessment of oak versus non-oak tree species dynamics, and further incorporation of both climatic and individual tree health indices (including pest damage).

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SOIL AND MINERAL NUTRITION

EARLY UNDERSTORY BIOMASS RESPONSE TO ORGANIC MATTER REMOVAL AND SOIL COMPACTION

Felix Ponder, Jr.[1]

Abstract.—In the Missouri Ozarks, 6 and 8 years after treatment, understory biomass differences between bole only harvesting (BO) and whole-tree plus forest floor harvesting were not different; neither were there understory biomass differences between no compaction and severe compaction. Separation of the biomass into broad species categories (trees, shrubs, annuals, perennials, grasses, woody vines, and annual vines) showed some categories to be different between treatments. Some differences in species abundance over time were also noteworthy. Understory vegetation is important to the survival and growth of the developing stand and has significant implications for wildlife populations, fuel loads, and nutrient cycling, all of which can be considered part of site productivity.

INTRODUCTION

The disturbance caused by forest management can alter physical, chemical, and biological soil properties in ways that could intensely affect soil productivity. Soil compaction (SC) and organic matter removal (OMR) have been identified as key factors influenced by forest management activities (Powers and others 1990). In 1989, the U.S. Forest Service initiated the world's largest coordinated effort to understand how soil disturbance affects long-term forest productivity and in 1990 the first Long-Term Soil Productivity Study (LTSP) sites were established (Powers and others 1989). This nationwide study, which also includes sites in Canada, focused on the impacts of OMR associated with harvesting, and site preparation for regeneration, as well as SC associated with equipment traffic during timber harvesting and site preparation (Stagg and Scott 2006). In a coordinated way, the study investigates how OMR and SC affect a site's ability to capture carbon and process it into dry matter.

The removal of organic matter removes biomass that would ordinarily be subjected to decomposition, potentially reducing site productivity by altering nutrient cycles, biological functions, and other soil processes. Soil compaction diminishes soil productivity by increasing soil bulk density and reducing soil porosity. These dual effects combine to reduce the exchange of water and air, thereby reducing root growth and nutrient uptake (Greacan and Sands 1980), and growth of crop (Fleming and others 2006) and noncrop vegetation (Stagg and Scott 2006).

The effects of SC and OMR (leaf litter) were demonstrated in a greenhouse study (Jordan and others 1999) that reported decreased plant height, dry weight, and N uptake of red oak (*Quercus rubra* L.) and scarlet oak (*Q. coccinea* Muencch.) after 6 months of growth under high SC. However, the presence or absence of forest litter did not affect any of the response variables. An increase in harvesting intensity would be expected to increase soluble nutrient losses and increase transport of particulate matter, ultimately decreasing site productivity. However, because soil nutrient supply and productivity in forests change relatively slowly, Wells and Jorgensen (1979) speculated that biomass-harvesting practices could likely be selected from rotation to rotation without serious risk of decline in soil productivity. While this hypothesis may be true, site productivity includes a measure of total aboveground biomass, of which

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competing vegetation or understory, noncrop vegetation may constitute most of the standing biomass in an artificially regenerating forest stand. Over the short term, substantial quantities of nutrient elements can be temporarily conserved in the regrowth of woody and herbaceous vegetation invading the site following harvesting and during the years of the regenerating process, making nutrients unavailable to the trees and possibly affecting their growth (Marks and Borman 1972).

OBJECTIVE

This paper explores how OMR and SC have affected understory biomass during the early years of tree growth in a regenerating forest stand in Missouri.

MATERIALS AND METHODS

Site Description

The study site is in the Missouri installation of the LTSP, which was established in 1994. This site is located in the Carr Creek State Forest in Shannon County, MO. The silt loam soils on the site are primarily of the Clarksville series (loamy-skeletal, mixed mesic Typic Paledults). Initial soil chemical properties of the 0-30 cm depth were: pH (1:1 water) 5.7; total C, 3.3 percent; total N, 0.11 percent; P, 16.9 mg/kg; Ca, 789 mg/kg; and Mg, 61 mg/kg (Ponder and others 2000). Prior to harvest, the site had a well stocked, mature, second-growth oak-hickory (*Carya* spp.) forest with a site index for 50-year-old black oak (*Q. velutina* Lam.) that ranged from 22.5 to 24.3 meters (Hahn 1991). Mean annual precipitation and temperature are 112 cm and 13.3 ^{o}C, respectively (Barnton 1993).

Experimental Design

The LTSP study involves nine treatments derived from combinations of three levels each of organic matter removal and soil compaction. The three levels of organic matter removal were as follows: 1) merchantable tree boles removed, crowns retained, understory felled, and forest floor not removed (BO); 2) whole tree and all aboveground living vegetation removed, forest floor retained (WT); and 3) all surface organic matter removed, including whole tree, dead and living vegetation plus forest floor, exposing mineral soil (WT+FF). Merchantable boles were trees with diameters at breast height (d.b.h.) of 25 cm or larger. The three levels of compaction were: 1) no compaction (NSC); 2) moderate compaction (MSC); and 3) severe compaction (SSC). Soil compaction was accomplished by using heavy road construction equipment (Ponder and Mikkelson 1995). Mean bulk density increased to 1.8 g cm^{-3} in SSC treatment compared to 1.3 g cm^{-3} for the NSC treatment.

The 3 x 3 factorial arrangement of treatments was replicated three times. Three uncut control plots, which were similar in stand history, species composition, and topography to harvested plots, were established as reference plots. Prior to tree harvesting and treatment installation, pre-harvest inventories of the overstory, understory, herbaceous layer, and dead and downed woody material, plus biomass and soil sampling were completed. After treatment installation, 1-0 seedlings of red oak, white oak (*Q. alba* L.), and shortleaf pine (*Pinus echinata* Mill.) were planted in rows at 3.66 m intervals at a ratio of three oaks of each oak species to one shortleaf pine. A complete description of the site and the LTSP installation are provided elsewhere (Ponder and Mikkelson 1995).

For this report, only the high and low treatments of OMR and SC were used to compare aboveground biomass and nutrient measurements. Organic matter removal treatments removed 84.6 and 228.2 Mg ha^{-1} of biomass respectively, for BO and WT+FF. For the first 2 years after planting, a 0.9-m radius area around seedlings was sprayed annually in the spring with a mixture of glyphosate and simazine to control weeds. Growth responses to weed control are not part of this report.

Seedling height and diameter were measured after planting and annually thereafter. Diameter at 2.54 cm above the soil surface and when trees reached 1.4 m tall or taller, were measured. Beginning in 1999, year 6 of the study, and continuing annually, understory plants were inventoried in 7.9-m^2 permanent circular subplots where weeds were not controlled. Three subplots were established in each of the three replicates for the nine treatments for a total of 81 subplots. Plants were inventoried by species and counted and their heights measured. All subsamples were oven-dried for 48 hours, and weighed. Data were collected between early July and mid-August. Vegetation samples were later quantified into groups of woody plants (trees, shrubs, and woody vines) and herbaceous plants(annuals, perennials, and grasses). Plots were sampled randomly by blocks during each measurement period. For nutrient analyses, vegetation was clipped in three 0.30-m^2 sample areas located adjacent to each inventory subplot. Samples were oven-dried, and separated into leaves and stems; the stems were discarded before leaves were ground in a Wiley mill to pass through a 2-mm sieve. Samples were analyzed for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) at the University of Arkansas Agricultural Diagnostic Laboratory in Fayetteville, AR. Total N was determined by combustion using a LECO CN 200 (LECO Corp., St. Joseph, MI) and P, K, Ca, and Mg was determined in HNO_3 digest on ICP.

Statistical Analyses

The experiment was analyzed as a randomized complete block design. Data were analyzed using analysis of variance with the PROC GLM procedures in SAS Version 8.2 (SAS Institute, Cary, NC). All statistical tests were performed at the $\alpha = 0.05$ level of significance.

RESULTS AND DISCUSSION

Biomass

Treatment differences for OMR and SC between understory biomass separated into groups of woody and nonwoody plants were not different for either measurement period (Table 1). Understory biomass followed the order of severe soil compaction > bole only > whole tree+forest floor removal > no soil compaction. The biomass for planted trees in year 8 averaged 38.2 and 36.7 Mg ha^{-1}, for bole only and whole tree+forest floor removal, respectively, and 36.0 and 37.7 Mg ha^{-1}, for no compaction and severe compaction, respectively (data on file at 208 Foster Hall, Lincoln University, Jefferson City, MO 65102). These values indicate that no adverse effect of OMR and SC on planted tree biomass was present. Similarly, Stagg and Scott (2006) reported that the biomass for planted loblolly pine was not significantly affected by soil compaction at age 5 yr or at age 10 yr. They did, however, report differences in the production of understory biomass between compaction treatments, indicating that the understory vegetation was much more susceptible to soil compaction than were the planted trees.

Height

Trees in the bole-only treatment were taller than trees in the whole tree+forest floor removal treatment for both measurement periods (Table 2). Both trees and woody vines were taller in the no soil compaction treatment than trees in the severe soil compaction treatment in year 6, but differences were not significant for year 8. Woody vines tended to be comparatively longer in no soil compaction plots than in severe soil compaction plots. The length of woody vines was likely associated with the taller shortleaf pines on these plots (Ponder, in press). Vines in trees were not actually measured, but their lengths were estimated.

Table 1—Mean understory of woody and non-woody biomass (Mg/ha)in response to two levels of organic matter removal (OMR) and soil compaction (SC) at 6 and 8 years of stand development.

Treatment[1]	Year 6			Year 8		
	Mean	S.Dev.	P>F	Mean	S. Dev.	P>F
Nonwoody						
BO	1.6	1.0	0.36	3.9	3.0	0.68
WT+FF	1.3	0.7		3.5	2.1	
NSC	1.5	0.8	0.83	2.6	1.8	0.67
SSC	1.6	0.6		4.1	2.2	
Woody						
BO	1.5	1.1	0.83	2.2	1.1	0.39
WT+FF	2.3	1.5		2.1	1.4	
NSC	2.1	0.8	0.40	2.9	1.2	0.75
NSC	0.8	0.5		2.1	1.4	
Combined						
BO	1.5	1.1	0.91	3.1	2.6	0.78
WT+FF	1.6	0.7		2.8	2.2	
NSC	1.5	0.9	0.93	3.0	2.4	0.92
NSC	1.5	0.8		3.1	1.6	

[1]BO=bole only removed, WT+FF=whole tree+forest floor removed, NSC=no soil compaction, and SSC=severe soil compaction

Number of Plants

With few exceptions, the overall number of plants declined from year 6 to year 8 in most species groups (Table 2). The number of trees was higher for whole tree+forest floor removal than for bole only for year 6 and for no soil compaction than for severe soil compaction in years 6 and 8. Shrub and grass count also tended to be higher for severe soil compaction treatments than for the no soil compaction treatment. The implication is that soil disturbance can initially increase the number of plants, but competition for aboveground and belowground resources will likely affect their surviorship in later years.

The total number of plants declined from year 6 to year 8 (Table 2). With some exceptions, trees and shrubs that were in the highest number in year 6 continued to be high in year 8. Differences in the number of trees and shrubs between the no compaction treatment and the severe compaction treatments declined from 27 percent in year 6 to 14 percent in year 8. Overall, as the number of trees increased, grasses decreased by 60 percent from year 6 to year 8. Additionally, trees and shrubs responded differently to soil compaction. Both sassafras (*Sassafras albidum* (Nutt.) Nees) and dogwood (*Cornus* spp.) were in higher numbers in the no compaction treatment than in the severe compaction. On the other hand, the number of shortleaf pine tended to be higher in the severe compaction treatment compared to their number in the no compaction treatment while the opposite was the case for hickory. But the difference in numbers between treatments for hickory in year 8 suggests that the trend may be short lived.

Corns (1988) speculated that negative effects of compaction continue for a time, but as soils gradually revert to its precompaction levels, the physiological effect of soil compaction on plants may subside. By year 8 of this study, surface soil (0 to 10 cm) bulk density had recovered to precompaction level, while

Table 2.—Mean height and vegetation density (counts/plot) for trees, shrubs, annuals, perennials, grasses, woody vines, and annual vines in hardwood understory in response to two levels of organic matter removal (OMR) and soil compaction (SC) after 6 and 8 years of stand development

	OMR[1]				SC[2]			
Species group	BO	WT+FF	BO	WT+FF	None	Severe	None	Severe
	Height		Density[3]		Height		Density	
	---- cm ----		Counts/plot		---- cm ----		Counts/plot	
Year 6								
Trees	5.6a[4]	4.7b	301a	415b	5.5a	4.9b	594a	300b
Shrubs	2.9	3.4	176	168	3.6	3.1	149a	209b
Annuals	2.7	2.6	222	183	5.0	6.2	114	165
Perennials	1.9	1.8	79	56	1.4	1.9	25	98
Grasses	1.8	1.7	196	241	1.5a	1.9b	151a	363b
Woody vines	3.5	3.1	246a	168b	3.7a	2.9b	241a	157b
Annual vines	1.1	1.3	21	59	1.1	1.3	45	49
Total	---	---	1241	1290	---	---	1319	1341
Year 8								
Trees	23.4a	18.9b	195	261	21.0	18.9	315a	184b
Shrubs	10.1	11.2	123	147	10.7	11.2	109	175
Annuals	7.0	6.1	142	134	5.0	6.2	114	165
Perennials	4.2	4.0	56	64	2.9	4.0	61	80
Grasses	3.7	3.4	66a	128b	3.0a	3.8b	66a	112b
Woody vines	10.8	7.8	144	127	10.6	8.2	161	92
Annual vines	2.2	3.2	6	10	2.3	2.2	12	5
Total	----	----	732	871	----	----	838	813

[1]BO=bole only removed, WT+FF=whole tree+forest floor removed.
[2]None=no soil compaction, Severe=severe soil compaction.
[3]Counts/per plot is the number of individuals recorded in 27, 7.9-m2 subplots.
[4]Means in a row for OMR or SC treatments within a year followed by different letters are significantly different at the 0.05 level based on Tukey's test.

bulk density differences between no compaction and severe compaction were still present for the 10- to 20-cm depth (data on file at 208 Foster Hall, Lincoln University, Jefferson City, MO 65102). Based on comparison with a number of these LTSP sites, Page-Dumroese and others (2006) concluded that the levels of compaction achieved, as measured by bulk density, were often of a similar magnitude to those reported for a variety of skid-trail studies, mimicking small-scale changes on large-scale plots. As vegetation develops on LTSP sites in response to SC treatments, investigators will be able to determine how applicable skid-trail studies are to larger areas and how recovery time is affected.

Disturbances such as OMR and SC play an important role in determining forest structure and species composition. Additionally, the development of plant communities will influence the type of wildlife using the site.

Disturbance that removes the overstory changes the amount of light that reaches the forest floor and increases the amount of nutrients available for new plants to utilize. In the present study, by year 8, mean nutrient concentrations in the understory vegetation on the site in this study did not differ among OMR and SC treatments (data not presented).

Soil disturbance typified by OMR and SC can decisively alter the seasonal soil moisture regime and plant-available water, but 5-year growth responses for western conifers growing in soils compacted to different levels were inconclusive (Gomez and others 2002). However, a significant increase in soil bulk density may not affect soil water (Froehlich and McNabb 1984). During compaction, micropores may be unaffected and soil porosity changes could be confined to the mesopore space (Startsev and McNabb 2001), resulting in little change in soil moisture content. In the present study, severe compaction generally resulted in increased moisture at 20 cm throughout the growing season during the first 5 years of the study (Page-Dumroese and others 2006). Machado and others (2003) reported that increased availability of soil resources (supply- demand) can affect understory vegetation growth, but the magnitude may depend on how tolerant plants are to shade.

CONCLUSIONS

Differences in understory dry weight for OMR and SC treatments were not detectable after 6 and 8 years of the study. Total understory biomass followed the order of SSC>BO>WT+FF>NSC. The total number of plants declined from year 6 to year 8, but the number of trees increased while grasses decreased by 60 percent from year 6 to year 8. Overall, while small differences within treatment categories (OMR and SC) were present, there does not appear to be any general adverse effect of OMR and SC on this regenerating stand. The adverse effects of soil compaction on the growth of forest vegetation are well documented, but some results show that some sites and tree species respond positively to compaction. No comparisons were made between the vegetative composition of other regenerating forests and the present site, but the lack of difference between BO and WT+FF in the present study suggest that the overall plant population would likely be similar to other regional regenerating forests following conventional harvesting. Studying understory biomass response to organic matter removal and soil compaction provides another opportunity to evaluate short- and long-term impacts of soil disturbance on forest stand development.

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EFFECT OF FERTILIZER TREATMENTS ON AN ALKALINE SOIL AND ON EARLY PERFORMANCE OF TWO BOTTOMLAND OAK SPECIES

Felix Ponder, Jr., Matthew John Kramer, and Freida Eivazi[1]

Abstract.—Many acres of once productive Missouri farmland along the Missouri River are being planted to bottomland hardwoods. Once trees become established on many of these sites, however, most show symptoms of chlorotis due to high pH levels (>7.5) in soil. Six treatments containing combinations of iron (Fe), sulfur (S), and nitrogen (N) were tested for their effectiveness in ameliorating soil conditions to stimulate nutrient uptake and growth of 2-year-old planted pin oak (*Quercus palustris*) and swamp white oak (*Q. bicolor*). Some chlorosis was still present after 2 years of treatment. Also, treatments with S had significantly (P>0.05) lower pH. Neither Fe nor N treatments affected pH. For leaf nutrient and growth analyses, tree species were not analyzed separately. Treatments with S had lower foliar phosphorus, potassium, and calcium concentrations for all years, but these concentrations were not affected by Fe or N. Deer browsing continues to be a major problem for maintaining height growth. Treatments containing S had smaller basal diameters and lower tree heights than treatments without S. Height loss or height decline, which may have been associated with deer browsing, was greater in treatments with S. Sulfur-containing fertilizers were effective in lowering soil pH, but the depression of pH by these fertilizers may not necessarily coincide with favorable seedling response. Nutrients other than Fe are likely involved in the seedling chlorosis. Prescriptions for nutrient management on bottomland sites such as these will need to be developed for tree plantings to become healthy, mast-producing forests.

INTRODUCTION

Many bottomland old fields planted to hardwoods do not successfully make the transition to becoming productive forests. Many hardwood plantings, including oak, on old field sites have demonstrated high mortality, high stem dieback, and slow growth rates. Studies show that healthy seedlings with large stem diameters (Johnson 1976) and root systems usually have good survival and better growth than smaller-diameter seedlings. More recently, Forest Keeling Nursery has made (root production method) RPM™ seedlings available (Lovelace 1998). RPM seedlings have massive root systems, and some hardwood species produce acorns by the third year under nursery conditions.

Poor weed control and soil fertility likely have contributed much to the poor performance of many failed tree plantings. Of particular interest for hardwood regeneration to enhance wildlife habitat are old crop fields in bottomlands of the Missouri River. The flood of 1993 in Missouri degraded more than 325,000 ha of cropland along the Lower Missouri River floodplain through scouring and the depositing of sand onto crop fields (Grossman and others 2003). The thick deposits of sand have lowered soil productivity so much that field crop production is no longer profitable. Attempts to artificially regenerate these bottomland fields have encountered some difficulty (Schweitzer and Stanturf 1997).

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Many of the soils on these floodplain bottomlands have high pH, high nutrient leaching, intense vegetative competition, and poor drainage, all of which reduce tree performance. When these sites are planted to hardwoods, including oaks, they exhibit leaf symptoms of iron (Fe) deficiency usually induced by poor drainage or by soils with a high calcium (Ca) content and pH levels above 7.5 (Courchesne and others 2005). These bottomland soils contain adequate amounts of mineral Fe, but as soil pH rises above 7.0, Fe changes to an insoluble form that many plants have difficulty taking up. Affected leaves turn to a yellowish color while leaf veins remain dark green. When not corrected, Fe deficiency can cause poor root development, severe stunting, and plant death. Mineral deficiencies other than Fe, such as nitrogen (N), phosphorus (P), magnesium (Mg), manganese (Mn), copper (Cu), zinc (Zn), or boron (B) may also result in chlorosis symptoms. Symptoms of Mg deficiency, in particular, may be similar to those of Fe deficiency. The two can be distinguished by broad bands of normal green color that remain next to the major vein if Mg is lacking. Furthermore, leaves on the ends of the branches of Mg-deficient trees generally are not affected until late in the summer after growth has stopped.

OBJECTIVES

Iron chlorosis is commonly alleviated by application of Fe sulfate and Fe chelates. This perennial problem may require several Fe applications per year (Ryan and others 1975). As Fe availability in calcareous soils is influenced by pH (Hodgson 1963), a reduction in soil pH through the use of acidifying amendments should, theoretically, eliminate chlorosis and make it unnecessary to repeat applications. In the study reported herein, various treatments of Fe, S, and N were broadcast-applied and compared after 2 years as to their effect on soil pH and nutrient uptake and growth of planted pin oak (*Quercus palustris*) and swamp white oak (*Q. bicolor*).

METHODS AND MATERIALS

Site

The study site is located on lands owned and managed by the Missouri Department of Conservation. Plowboy Bend Conservation Area is located at latitude 38° 48′ 5”N; longitude 92° 24′17”W in Moniteau County, MO. The area has undergone numerous soil-depositing floods over the years. The soil on the site is Sharpy fine sand (mixed, mesic, Typic Udispsamments). Sharpy soils are classified as hydric, meaning that they are periodically saturated, ponded, or flooded during the growing season.

In 2001, a total of 336 swamp white and pin oak seedlings were planted in a randomized block design in rows at 12 x 12-m spacing. Each block contained 12 pin oaks and 12 swamp white oaks that were of either bare root or RPM™ origin and were planted in mounded or unmounded rows. Combinations of iron, sulfur, and nitrogen were applied in the following treatments: 1) $FeSO_4$ plus water-degradable S; 2) Fe chelate; 3) Fe chelate plus NH_4NO_3; 4) NH_4NO_3 alone; 5) NH_4NO_3 plus $FeSO_4$; and 6) control. Ferrous sulfate was applied at a rate of 2,240 kg ha^{-1} or 336 g/tree, ammonium nitrate at 112 kg ha^{-1} actual N or 49.4 g/tree, Fe chelate (Sprint 330, Becker Underwood, Ames, IA) was applied at a rate of 454g/93 m^2 or 8 g/tree, and water-degradable S at 2,240 kg ha^{-1} or 336 g/tree. Each treatment was applied to 20 randomly selected RPM™ and bare-root trees annually in the spring since 2004. Fertilizer chemicals were broadcast-applied on top of the 1.3-m^2 woven plastic mat used to control weeds around each tree. Trees in the control treatment were not treated.

From each treatment, two soil samples were collected from half of the trees at 10 and 20 cm depths in the fall of 2004 and 2005. Samples were collected beneath the plastic mats approximately 61 cm from

Table 1.—Mean soil pH and nutrient concentrations for alkaline bottomland soil planted to pin oak (*Quercus palustris*) and swamp white oak (*Q. bicolor*) along the Missouri River following applications of soil amendments for 2 years.

Treatments	pH	P	K	Ca	Mg	S	Na	Fe	Mn	Zn	Cu	B
				----	----	----	mg/kg	----	----			
Year 1												
Without Fe	8.1	58	266	3156	284	11	21	415	79	4	3	3
With Fe	8.1	59	271	3378	331	13	20	416	77	4	3	3
Without S	8.1	58	288a	3575a	337a	13a	20	412	79	4	3a	3a
With S	8.2	60	226b	2671b	270b	10b	19	425	74	3b	2b	2b
Without N	8.1	58	276	3379	330	13	20	428	76	4	3	3
With N	8.2	59	262	3249	305	12	19	404	79	4	3	3
Year 2												
Without Fe	8.2	28	106	1722	150a	5a	6a	215	39	2	1	0.2
With Fe	8.1	28	105	1723	178b	14b	7b	233	37	2	1	0.2
Without S	8.2a	29	114a	1866a	165	55a	7	212a	38	2	1	0.2
With S	7.9b	26	86b	1402b	180	25b	6	264b	36	2	1	0.2
Without N	8.1	28	108	1758	174	15	7	232	37	2	1	0.2
With N	8.2	29	102	1677	165	7	6	223	38	2	1	0.3

[1]Different letters denote significant differences ($p<0.05$) between the two treatments for a nutrient.

the base of trees. Samples were oven-dried at 65 °C and sieved through a 4-mm sieve. For foliar nutrient determination, leaf samples were collected in late June to mid-July from the same trees where soil samples were collected. Samples were oven-dried at 65 °C and ground in a Wiley mill to pass through a 2-mm sieve. Samples were analyzed annually for macro-nutrients and micro-nutrients at a commercial laboratory (Agriculture Diagnostic Laboratory, Fayetteville, AR 72704). Height and basal diameter (db) at 2.5 cm from the soil surface and diameter at breast height (d.b.h.) have been measured annually.

We examined the effect of the presence or absence of Fe, S, and N on soil and leaf chemistry and tree growth. Tree species were not separated, nor were differences between mounded and unmounded trees or differences between the six treatments tested. Data were analyzed using analysis of variance, and differences between treatments were tested using Tukey's test.

RESULTS

Soil pH and Nutrients

Only S application significantly ($P<0.05$) affected soil nutrient concentrations both years and soil pH in the second year of the study (Table 1). Although differences were small for some micronutrients, differences between treatments with S and without S were significant. For most of these nutrients, extractable amounts were higher without S than with S. Nutrients that were affected included K, Ca, Mg, S, Zn, Cu, and B for year 1 and K, Ca, and S for year 2. Iron, however, was higher with S than without S for year 2. Soil pH was significantly lower with S than without S by year 2. While Fe did not affect soil pH or nutrient levels in year 1, the levels of extractable Mg, S, and sodium (Na) were higher with Fe than without Fe in year 2. Nitrogen did not significantly affect pH or soil nutrient levels in either year (Table 1).

Table 2.—Mean leaf nutrient concentrations for planted pin oak (*Quercus palustris*) and swamp white oak (*Q. bicolor*) on bottomland alkaline soils along the Missouri River following applications of soil amendments for 2 years.

Treatments	N	P	K	Ca	Mg	S	Na	Fe	Mn	Zn	Cu	B
	------------ Percent ------------						------------- mg/kg -----------					
Year 1												
Without Fe	2.0	0.2	0.7	1.2	0.2	0.1	42	79	183	47	10	17
With Fe	2.0	0.2	0.7	1.0	0.2	0.1	38	81	213	53	9	19
Without S	2.0	0.2a[1]	0.8a	1.2	0.2	0.1	41	78	136a	49	9	20
With S	2.0	0.1b	0.6b	0.9	0.2	0.1	36	85	355b	57	9	16
Without N	2.0a	0.2a	0.8	1.1	0.2	0.1	38	77	226	59a	9	19
With N	2.2b	0.1b	0.7	1.0	0.2	0.1	41	83	178	41b	9	18
Year 2												
Without Fe	1.9a	0.2	0.6	2.0	0.3	0.1	7	43	103	57	5	18
With Fe	2.2b	0.2	0.7	1.4	0.2	0.1	7	41	83	55	5	21
Without S	1.9	0.2	0.7	1.7a	0.2	0.1	8	45	68a	54	5	20
With S	2.1	0.2	0.7	1.1b	0.2	0.1	5	35	134b	59	5	20
Without N	1.9a	0.2a	0.7	1.6	0.2	0.1	7	41	97	61a	5	20
With N	2.1b	0.1b	0.7	1.4	0.2	0.1	6	42	78	49b	4	20

[1]Different letters denote significant differences (p<0.05) between the two treatments for a nutrient.

Leaf Nutrients

Foliar P and K were significantly (P<0.05) higher without S than with S in year 1 while Mn was higher with S than without S (Table 2) in years 1 and 2. Calcium was higher without S than with S in year 2. Foliar N was higher with N both years while P and Zn were higher without N than with N for both years. Except for higher foliar N with N than without N in year 2, nutrient differences betweeen N treatments were not significant.

Tree Growth

Tree growth according to bd, d.b.h., and height was not statistically different between treatments for any of the three nutrients used (data not shown). Mean bd was 1.2 and 1.4 cm without Fe and N compared to 1.6 and 1.5 cm with Fe and N, respectively, while bd was 1.7 cm without S and 1.3 cm with S. Height decline was -0.6, -0.3, and -0.4 m without Fe, S, and N, respectively, compared to -0.2, -0.5, and -0.1 m with Fe, S, and N, respectively.

DISCUSSION

The alkaline pH (>8.0) of the soil on the bottomland site in this study is likely due to the alkalinity of water and sediments of limestone origin that have frequented this landscape over the years during floods (Stallings 1994). Alkaline soils are affected by the lack of nutrient solubility, thereby causing essential elements to become unavailable for plant uptake (Wallace and Lunt 1960). For example, the solubility of Fe at pH 4.0 is 100 ppm but if the pH is increased to 6.0, the solubility drops to 0.01 ppm. Fe solubility is often too low to sustain healthy plant growth above a pH of 7.5. In the present study, the addition of Fe and N without a change in soil pH did not affect the extractable amounts of either nutrient, but the lowering of the pH in year 2 with S resulted in a corresponding increase in extractable Fe (Table 1). The crucial question in the application of fertilizers to soil is the longevity of the effect. All nutrients were applied at recommended rates, but because they were broadcast-applied and their solubility or ability to cause change in the soil was left to be accomplished by the spring rains, losses due to leaching and/or volatilization could be excessive. Because nutrient analyses were done annually rather than at one time, it cannot be determined whether the overall lower values for year 2 represent "actual" lower soil values (Table 1) or result from equipment settings for standardization during the analyses. However, the magnitude of the difference in nutrients between years was not comparable for pH.

The extractable amount of several soil nutrients, K, Ca, Mg, and S, was lower with S than without S. However, while the overall extractable S for both years was higher for the treatment without S than with S, when soils were separated by depths (10 and 20 cm), treatments with S had more S than treatments without S regardless of soil depth (data on file at 208 Foster Hall, Lincoln University, Jefferson City, MO 65102). This result is likely associated with the soil acidification process (Courchesne and others 2005). During the acidification process the decrease in pH leads to the release of these positively charged ions increasing their concentrations in the soil solution. However, once the cation exchange surface has been depleted of these ions, their concentrations in the soil solution can become low and are primarily determined by the weathering rate. Although our site is being artificially regenerated, the decrease in soil nutrient cation reserves in unmanaged and undisturbed forests has been attributed to a range of ecosystem processes. Some of these processes pertain to our results, including recent changes in the concentration of base cations in atmospheric deposition (Driscoll and others 1989, Wessenlink and others 1995), soil leaching by acidic compounds of anthropogenic or natural origin (Richter and others 1994, Kirchner and Lydersen 1995), and elemental sequestration in biomass (Binkley and others 1989, Knoepp and Swank 1994, Trettin and others 1999). Rustad and others (1993) reported increased leaching of S and N in soils treated with S and N, accompanied by increased losses of base cations during 2 years of acidification. David and others (1990) and Mitchell and others (1994) reported a concomitant decline in soil pH accompanied by increased sorption of S. In another study using coarse loamy soil, Rustad and others (1996) reported no significant decreases in base cations after 4 years and a small pH decline in the high-S treatment. The reported decline in pH was largely attributed to the significant increase in the concentration of exchangeable Al.

The amount of plant-available nutrients is much harder to determine than the amount of extractable nutrients; foliar nutrient uptake differences may appear to be only loosely related to soil nutrient levels (Tables 1 and 2). Several significant differences in foliar nutrient levels were associated with treatments containing Fe and N. In years l and 2, N and P were higher and Zn was lower in treatments containing N (Table 2). The addition of S was associated with lower P and K in year 1 and Ca in Year 2. Foliar Mn was doubled or more in treatments containing S. Chlorotic leaves developed on all trees, some becoming necrotic before leaf fall. Leaf nutrient analysis was not used to investigate the chemical conditions associated with chlorosis. Mills and Jones (1996) reported the following range of macronutrient element values (percent) for pin and swamp oaks from their survey of apparently healthy forest trees: N, 1.0-2.3; P, 0.2-0.4; K, 0.8-1.3; Ca, 0.4-1.4; Mg, 0.1-0.3; and S, ~0.2, respectively. These authors also reported the following range of micronutrient values (mg/kg) for pin oak: Fe, 45-180; Mn, 218-633; Zn, 29-88; Cu, 7-38; and B, 19-122. The comparison between our data and the survey data indicated that several of the nutrient elements for leaves in our report are less than or in the lower end of the survey range. Except for Zn, this observation includes all of the micronutrients, particularly S and Mn. Messenger (1991) reported that pin oak leaves with uniform chlorosis had low concentrations of N (1.48 percent), S (0.1 percent), P (0.07 percent), Zn (31 mg/kg), and Cu (4.6 mg/kg) which were significantly different from the concentrations in the green leaves. The interveinally chlorotic leaves, on the other hand, had either lower or similar N concentrations, but did not have low S, P, and Cu concentrations compared to green leaves.

In summary, fertilizer treatments did not increase tree growth. All trees were repeatedly browsed by deer; therefore, any trends in growth differences might have been influenced by deer activity. Treatments with S had lower soil pH and trees had higher leaf Mn. Trees in treatments with N had higher leaf N. Obviously, we have not determined that lowering soil pH will effectively increase overall nutrient uptake, alleviating chlorosis and increasing tree growth. Without fencing, it will be difficult to determine growth response. The study is ongoing with plans to measure the chemistry of soil and foliage, including chlorophyll content, over the growing season. These measurements should help to determine the duration of treatment effects on soil and leaves.

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EFFECTS OF MOISTURE AND NITROGEN STRESS ON GAS EXCHANGE AND NUTRIENT RESORPTION IN *QUERCUS RUBRA* SEEDLINGS

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Abstract.—The effects of simulated soil fertility at three levels (poor, medium, and rich soils) and moisture stress at two levels (well watered versus moisture stressed) on gas exchange and foliar nutrient resorption in 1+0 bareroot northern red oak (*Quercus rubra*) seedlings were evaluated. Current nitrogen (N) uptake was labeled with the stable isotope ^{15}N to enable discrimination and quantification of the different N pools in new growth of plants, and the proportion remobilized and/or resorbed following senescence. Predawn leaf xylem water potential (Ψ_L) was -0.92 MPa in stressed plants and -0.76 MPa in well watered seedlings. Photosynthetic assimilation (A), stomatal conductance (gs), and transpiration (E) decreased with moisture and nutrient stress. Gas exchange rates were higher in well watered plants than in stressed plants. Simulated soil fertility increased A by 38 percent, E by 40 percent, and g_s by 50 percent in seedlings grown on the rich soil relative to those established on the poor soil. Seventy percent of N was resorbed in leaves of well watered plants compared to 47 percent in leaves of stressed plants. Resorption efficiency was 70 percent on the poor soil, but decreased to 40 percent on the rich soil. Increased foliar N resorption at low fertility suggests that the resorption process may have evolved as an important nutrient conservation strategy on infertile soils.

INTRODUCTION

Foliar nutrient resorption is an important nutrient conservation mechanism in deciduous forest ecosystems because the process may withdraw about 50 to 90 percent of the nutrients from senesced leaves for storage in plant tissues (Aerts 1996, Tagliavini and others 1998). However, the importance and underlying mechanisms of nutrient resorption and retention in plant tissues, and remobilization for new growth, are not well elucidated for northern red oak (*Quercus rubra*) seedlings. Additionally, the significance of the interactive effects of moisture and nutrient stress on red oak physiology, and on nutrient resorption efficiency, which is defined as percent N reduction between green and senesced leaves (Killingbeck 1996, Teklay 2004, Singh and others 2005, Yuan and others 2005), is not well studied. Moreover, how soil fertility might regulate resorption efficiency in red oak has yet to be elucidated. A better understanding of how moisture and nutrients might interact to influence physiological processes and resorption efficiency in red oak may be used to help manipulate plants at the nursery stage to increase nutrient retention in tissues for later utilization to benefit early establishment success of out-planted seedlings (Birge and others 2006, Salifu and Jacobs 2006).

OBJECTIVE

The objective of this study was to evaluate the effects of moisture stress and simulated soil fertility on gas exchange and N resorption in red oak seedlings. We hypothesized that resorption efficiency will increase on poor soils, but diminish on rich soils, following a nutrient conservation strategy on infertile soils. Northern

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red oak is selected for this study because of its economic importance and increased use in environmental plantings in the Central Hardwood Forest Region of the United States (Jacobs and others 2004).

MATERIALS

Materials and Growth Conditions

Bareroot northern red oak seedlings were grown from acorns for 1 year under operational conditions at the Vallonia State Nursery (38°85′N, 86°10′W) south of Indianapolis, IN, based on procedures described in Jacobs (2003). For the current study, 1-year-old bareroot red oak seedlings were obtained from Vallonia State Nursery and transplanted in sand culture using 6.2-l Treepots™ (Stuewe and Sons, Corvallis, OR). The potting soil consisted of 4:1:1 (sand:vermiculite:perlite). Plants were grown in the Department of Horticulture and Landscape Architecture Plant Growth Facility at Purdue University, West Lafayette, IN (40°25′N, 86°55′W). Mean day and night temperatures in the greenhouse were of 24 °C and 20 °C, respectively, under ambient light conditions.

Transplanted seedlings received one of three fertilizer rates: 0 [control], 500, or 1,000 mg N plant^{-1}, simulating poor, medium, and rich soils, respectively. The 500 and 1000 mg N plant^{-1} rates approximated 125 and 250 kg N ha^{-1}, respectively, under field conditions based on the weight of soil in pots (8 kg) in relation to silvicultural prescriptions under field conditions (Brady and Weil 2002, Salifu and Timmer 2003). Nitrogen was supplied with the irrigation as $[^{15}NH_4]_2SO_4$ enriched to five atoms percent ^{15}N (34-0-0, ISOTEC, Inc.). Current N uptake was labeled with the stable isotope ^{15}N, which allowed discrimination and quantification of the different N pools (labeled vs. unlabeled N) in new growth. Chelated micronutrients were applied at the rate of 0.08 g l^{-1} and phosphorus (P) supplemented by KH_2 P_2O_5 (0-52-34, Plant Products Co. Ltd., Brampton Ont.) at the rate of 30 kg P ha^{-1}.to avert deficiency of other nutrients. Plants were exposed to water stress treatments at two levels (well watered versus moisture stressed). Well watered plants were those that were irrigated back to container capacity (White and Mastalerz 1966) three times a week. Moisture-stressed plants were supplied irrigation only once per week, which approximates one-third of the total irrigation received by well watered seedlings. The third irrigation schedule for well watered plants coincided with that for moisture-stressed seedlings. Thus, moisture-stressed seedlings were watered using container capacity determinations from the third watering regime for well watered plants. Pots were periodically weight to determine the amount of water to be added (150 to 200 ml pot^{-1}) to bring pots back to container capacity.

Seedlings flushed one week after planting at which time fertilization commenced. Five equal split applications were conducted at weekly intervals for the first 5 weeks following flushing to improve uptake efficiency. Fertilizer was dissolved in the desired amount of irrigation and supplied to plants once a week.

Experimental Design, Plant Sampling and Chemical Analyses

The experimental design was a 2 x 3 factorial design testing moisture stress at two levels and simulated soil fertility at three levels, which was replicated three times. Foliar samples were collected from plants at two time periods: in mid-August (3 months after planting), when leaves were green and fully mature; and in November, when leaves senesced. Individual plants were enclosed in a plastic wire mesh to collect senesced leaves. Foliar data were processed for total N and ^{15}N analyses following protocols detailed in Rundel and others (1989). Total N and ^{15}N were determined using a Stable Isotope Mass Spectrometer coupled to a Micro-Dumas Elemental analyzer at the Stable Isotope Laboratory located at the University of Georgia, Athens, GA. Nitrogen resorption efficiency was calculated based on procedures described by Teklay (2004) and Yuan and others (2005) as shown in the following equation:

$$Re\ sorption\ Efficiency\ (\%) = \left[\frac{N_g - N_s}{N_g}\right] \times 100$$

Where N_g, is total leaf N (mg $plant^{-1}$) in green and mature leaves collected prior to senescence and N_s is total leaf N (mg $plant^{-1}$) in senesced leaves.

Mid-day leaf gas exchange was measured on three plants per treatment in mid-August. Net photosynthesis, stomatal conductance, and transpiration were measured with LI-6400 portable infrared gas analyzer equipped with a red LED light source and a CO_2 mixer control unit (LI-COR Inc., NE). Measurements were taken on the second fully formed leaf moving basipetally from the terminal point of the second flush. External light, provided by an LED red light source (LI6400-02) built into the top of the leaf chamber, was set to ambient greenhouse light intensity during measurements. CO_2 was controlled with the LI-6400 CO_2 injection system. Relative humidity was maintained at 55 to 65 percent. Leaf temperature was maintained at ambient conditions (28 to 30 °C). Pre-dawn Ψ_L was measured a day following gas exchange measurements. Leaf xylem water potential was measured with a pressure chamber (Model 600, PMS Instruments, Inc., Corvallis, OR).

Gas exchange, Ψ_L, and resorption efficiency data were evaluated using analysis of variance and effects tested at $P < 0.05$. Significant treatment means were ranked according to Tukey's HSD test at alpha =0.05. No significant treatment interaction effect was observed between simulated soil fertility x moisture stress treatments.

RESULTS AND DISCUSSION

Moisture stress significantly affected gas exchange parameters, but not plant water potential (Table 1). For example, relative to water-stressed plants, increases in net photosynthesis (85 percent), transpiration (126 percent) and stomatal conductance (160 percent) were observed in well watered seedlings. Similarly, simulated soil fertility treatments increased net photosynthesis (38 percent), transpiration (40 percent) and stomatal conductance (50 percent) in seedlings grown on the rich soil relative to those established on the poor soil although the differences were not statistically significant (Table 1). By contrast, simulated soil fertility treatments significantly influenced plant water potential. Foliar N resorption efficiency was significantly higher ($P< 0.0016$) in well watered plants (70 percent in comparison with moisture stressed seedlings (47 percent)(Fig. 1). Simulated soil fertility significantly affected foliar N resorption ($P < 0.0027$), which was greater at lower soil fertility, but declined with increasing nutrient input (Fig. 1). For instance, resorption efficiency was 70, 65, and 40 percent on respective poor, medium, and rich soils. Diminished foliar N resorption with soil fertility suggests the resorption process may have evolved as a mechanism for N conservation at low soil fertility.

The higher foliar N resorption efficiency noted for red oak in the current study compares well with about 50 to 90 percent suggested for hardwoods (Aerts 1996, Tagliavini and others 1998, Duchesne and others 2001). This high efficiency has important implications for nutrient loading of hardwoods (Birge and others 2006, Salifu and Jacobs 2006) to build nutrient reserves for subsequent utilization. Higher resorption suggests significant quantities of nutrients may be withdrawn from leaves of loaded seedlings into storage

Table 1.—Mean (SE) of physiological responses of red oak seedlings to moisture and nitrogen stresses grown in greenhouse environments for 6 months.

Treatments	A ($\mu molm^{-2}s^{-1}$)	E (mmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	Ψ(MPa)
Well watered	9.56 (0.72)a	4.03 (0.44)a	0.13 (0.02)a	-0.48 (0.05)a
Moisture-stressed	5.16 (0.50)b	1.78 (0.19)b	0.05 (0.01)b	-0.54 (0.05)a
Simulated soil fertility				
Poor	6.03 (1.15)a	2.21 (0.52)a	0.06 (0.02)a	-0.44 (0.03)b
Medium	7.72 (1.31)a	3.43 (0.83)a	0.11 (0.03)a	-0.64 (0.04)a
Rich	8.34 (1.06)a	3.09 (0.43)a	0.09 (0.02)a	-0.45 (0.05)b
P< F				
Moisture	0.0002	0.0002	0.0005	0.2911
Simulated fertility	0.0963	0.0925	0.1440	0.0109

Column means followed by different letters within treatment differ significantly according to Tukey's HSD test at α =0.05.

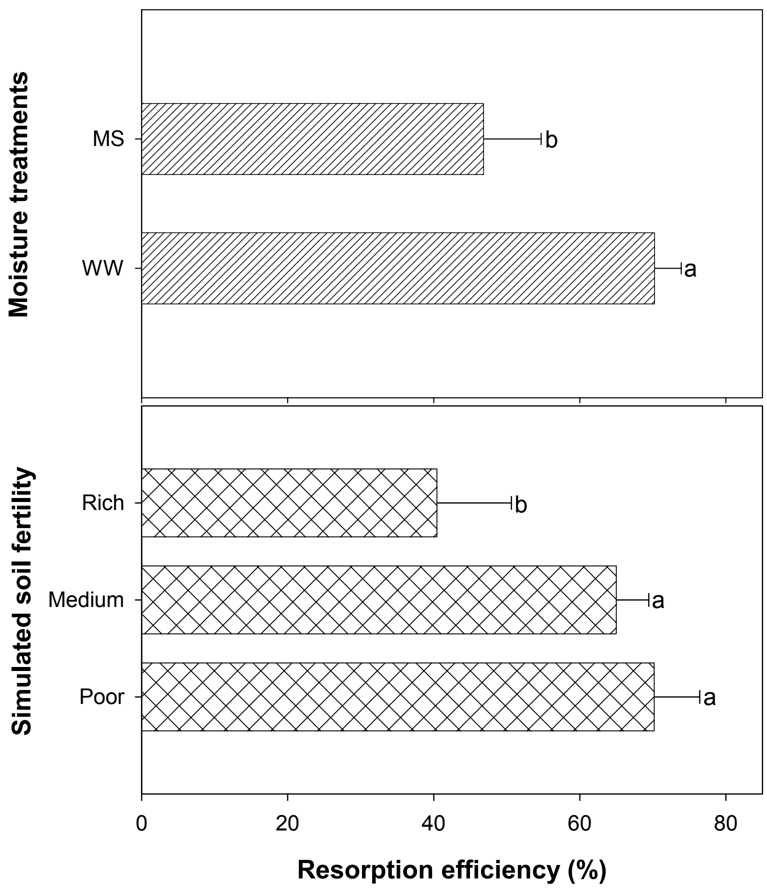

Figure 1.—Mean foliar resorption efficiency in red oak seedlings in response to moisture and nitrogen stress treatments under controlled greenhouse conditions. Plants were well water (WW), or exposed to moisture stress (MS), and unfertilized (poor soil), or received 500 mg N plant^{-1} (medium soil), or 1,000 mg N plant^{-1} (rich soil). Error bars indicate standard error of the mean estimate. Bars marked with same letters within treatment are not statistically different according to Tukey's highly significant difference test at α = 0.05.

tissues prior to senescence to benefit future growth. It is suggested that roots and shoots serve as important sinks for N storage during senescence (Dickson 1989, Lacointe and others 1994, Duchesne and others 2001), and sources for N in new growth in spring (Dickson 1989). Thus, conserved nutrients may be drawn upon immediately in spring to meet increased sink demand, especially for red oak during episodic growth events (Reich and others 1980, Crow 1988, Dickson and others 2000). Data (unpublished) to be generated by quantifying the various N pools in the plant-soil system will be used to further explore morphological and physiological mechanisms in relation to how moisture and simulated soil fertility might interact to influence N remobilization, resorption and utilization in new growth of red oak seedlings. Understanding of the proportional contribution of the various N pools in new growth will enable us to identify the most important N pool, which can then be manipulated to enhance plant response. In summary, results suggest red oak may withdraw between 40 and 70 percent of nutrients from foliage into storage tissues prior to senescence. Conserved N will likely serve as a critical N source for remobilization in spring (Cheng and Fuchigami 2002, Salifu and Timmer 2003) to benefit survival, growth, and early establishment success following field transplant.

ACKNOWLEDGMENTS

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INFLUENCE OF MICROTOPOGRAPHY ON SOIL CHEMISTRY AND UNDERSTORY RIPARIAN VEGETATION

Irene M. Unger and Rose-Marie Muzika[1]

Abstract.—The success of riparian forest restoration efforts depends in part on an understanding of the relationship between soil characteristics and vegetation patterns and how these change with site conditions. To examine these relationships for floodplains in northern Missouri, we chose three unchannelized streams as study areas. A sampling grid was established at two plots within each site for characterization of understory vegetation and collection of soil samples for chemical analysis. Microtopographical characterization was conducted using standard survey equipment. Relationships between microtopography and soil chemistry were weak but significant. Slope and elevation explained 15 percent of the variation observed in nitrate and 41 percent of the variation observed in both total C and total N. Vegetational components of the understory (herbaceous species and woody seedlings) were analyzed separately for association with soil chemistry and microtopography. Total N content of the soil explained 28 percent of the variation observed in total herbaceous cover and 41 percent of the variation observed in woody stems. When we considered microtopography, a multiple regression of flow accumulation and slope best predicted vegetational observations. These two variables explained 38 percent of the variation in herbaceous cover and 40 percent of the variation observed in woody stems.

INTRODUCTION

With the growing awareness of the importance of wetland services, preservation and restoration of wetlands has become an increasingly important focus in ecology. If these efforts are to be successful, however, understanding abiotic influences, such as topography and soil characteristics, on vegetational patterns is essential. While the influence of site on vegetation is more easily understood in upland forests, flooding can obscure patterns in riparian systems. Flood frequency, intensity, and duration will vary according to stream order and watershed size. Within a watershed, position on the landscape is important; as distance from river increases, particularly when moving from bottomlands to upslope positions, the frequency, intensity, and duration of flooding decrease. Differences in soil and vegetation would be expected with these gradients.

Studies of riparian systems indicate plant species distributions correlate with soil morphological and microtopographical variations (Beatty 1984, Grell and others 2005, Holmes and others 2005, Lyon and Gross 2005, Nilsson and others 1994, Ohmann and Spies 1998). Beatty (1984) found that forest floor microrelief could explain distributions of the most common herbs and woody seedlings in maple-beech forests of eastern New York. Grell and others (2005) concluded that differences in vegetation were primarily the result of subtle elevational variation within bottomland old-growth *Pinus taeda* forests of southern Arkansas. Holmes and others (2005) observed differences in ground-flora composition between floodplain and upland landforms in north-central Ohio. However, Becker (1999) found that environmental variables affecting vegetation distribution differed depending on the creek of interest. Lower-order Ozark streams(1st and 2nd order) in this study were influenced by bedrock, parent material, pH of the A horizon

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and waterway position, while higher-order Ozark streams (3rd - 5th) were influenced by landform features, pH of the A horizon, and soil texture characteristics (Becker 1999). In addition, several studies found that species associations shift along key environmental gradients, but different forest layers do not necessarily shift in concert. Site heterogeneity was a likely contributing factor to this differential response (Lyon and Gross 2005, Lyon and Sagers 1998, Sagers and Lyon 1997). Collectively, these results illustrate the need to study multiple watersheds within a region and the need to include multiple layers and especially herbaceous species in all characterizations of riparian forests.

OBJECTIVES

Riparian forests in the river hills of north-central Missouri have not been investigated for these relationships. The river hills exhibit different environments, topographies, and soils from the Ozarks, where these relationships have been previously investigated (Becker 1999, Lyon and Sagers 1998, Lyon and Sagers 2002, Sagers and Lyon 1997). Topographic dissimilarities between the river hills and the Ozarks are expected to result in unique relationships between flooding, soil chemistry, and riparian forest understory composition. Specific objectives of this research include: 1) to determine how microtopographical relief affects soil characteristics such as inorganic-N and total soluble polyphenolic content; and 2) to determine how understory vegetation (herbaceous and shrub layers) changes with microtopographical relief and soil characteristics.

STUDY AREAS

This study was conducted in the Central Dissected Till Plains of Missouri; this ecoregion covers almost all of Missouri north of the Missouri River (Nigh and Schroeder 2002). Floodplains along three streams in the northwest section of this ecoregion were selected: Locust Creek (Pershing State Park), Yellow Creek (Yellow Creek Conservation Area), and Thompson River (Crowder State Park) (Fig. 1). These are all second-order streams and tributaries of the Grand River. Study plots were positioned along forested unchannelized sections of each stream.

METHODS

Sampling Plots

At each stream, two plots, 100 m apart (the second downstream from the first), were established. Plots were 30 m x 30 m and consisted of a grid of eight transect lines: four transects oriented parallel to the stream and four transects oriented perpendicular to the stream. The transect closest to the stream was at 20 m from the water's edge and all transects were 10 m apart. Transect lines perpendicular to the stream were likewise 10 m apart. A 1-m^2 understory sampling quadrat was established at each intersection of the transect lines, yielding a total of 16 quadrats per plot at each of the floodplain sites.

Floodplain Characteristics

Topographical maps and preliminary observations revealed little relief in the areas chosen for this study. In order to determine site microrelief, survey equipment was used to measure changes in ground-level (i.e., elevation) as compared to a reference location (reference height = 100 cm). Elevation measurements were taken at each quadrat, at locations mid-way between quadrats and at locations 5 m outside the quadrats (i.e., around the perimeter of the study plot), for a total of 81 measurements per plot. These measurements were then used to calculate planform, flow accumulation (FA), and slope for each quadrat using ArcGIS (Environmental Research Systems, Redlands, CA). Planform is a measure of the change in slope perpendicular to the slope direction. A negative planform value indicates that the surface is concave

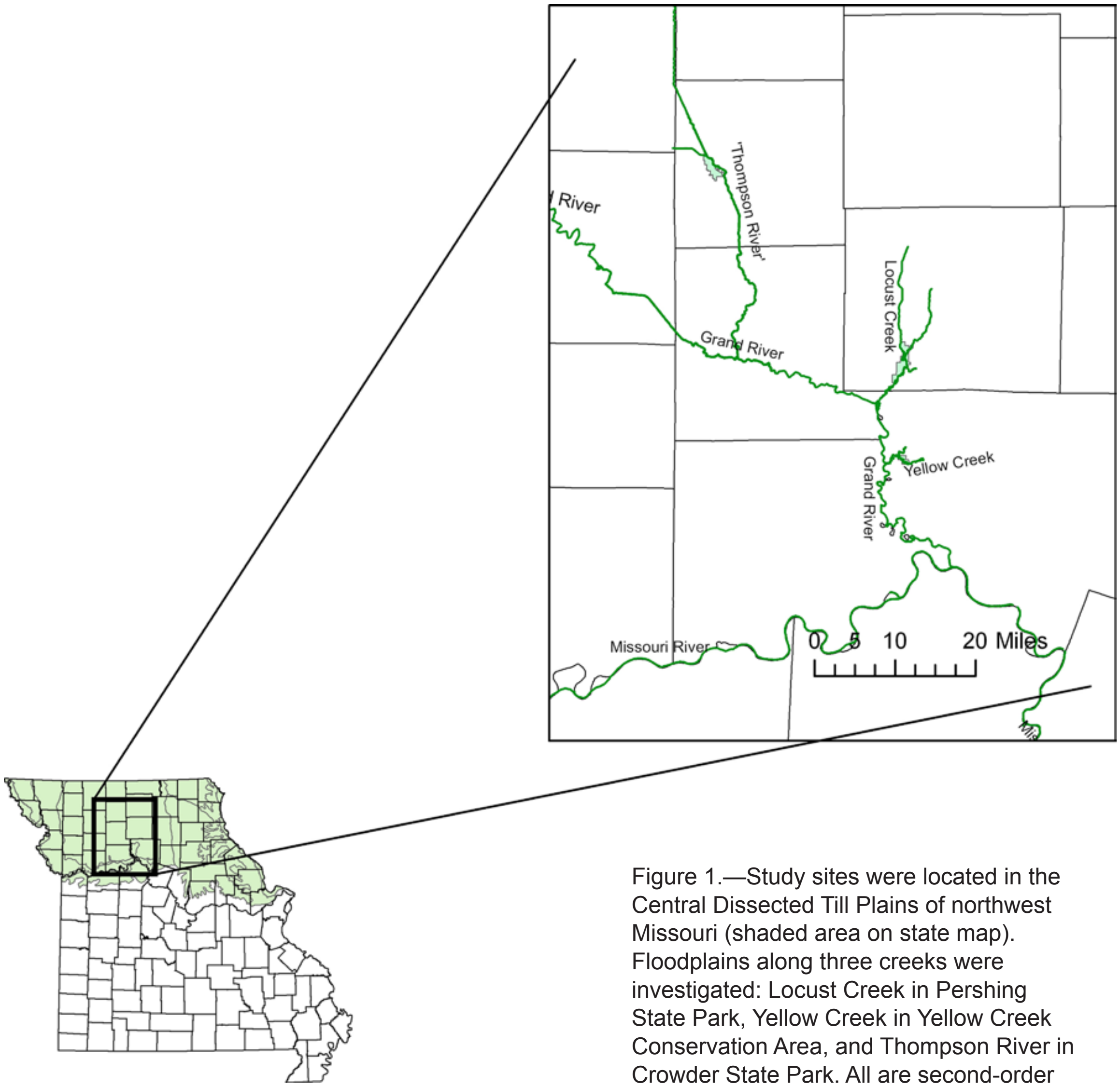

Figure 1.—Study sites were located in the Central Dissected Till Plains of northwest Missouri (shaded area on state map). Floodplains along three creeks were investigated: Locust Creek in Pershing State Park, Yellow Creek in Yellow Creek Conservation Area, and Thompson River in Crowder State Park. All are second-order streams and tributaries of the Grand River.

at that cell, while a positive value indicates that the surface is convex at that cell (Gallant and Wilson 2000). Since planform describes relative convexity and concavity (Gallant and Wilson 2000), it could be used to describe areas of water accumulation in a landscape. Flow accumulation is a measurement of the volume of water flowing into (or collected by) the quadrat; the higher the value, the greater the water flow into the cell (Sharma and others 2006). Slope (in degree) is a measure of the change of elevation between each quadrat and its neighbors (Sharma and others 2006). Slope affects the velocity of water movement and thus would have an impact on the transport of sediment and dissolved substances. A greater velocity results in increased transport of substances. Together these measures provide an indication of places in the landscape where water might be expected to accumulate and thus have an impact on soil nutrient cycling and vegetative growth.

Soil Sampling

Composite surface soil samples were collected at each quadrat in early June 2006. The top 20 cm of soil was collected from the center and the four corners of each 1-m^2 quadrat with a push-probe; these samples were mixed together to create a single sample per quadrat. Samples were placed in a cooler in the field and then frozen upon return to the lab. Samples were later freeze-dried, ground, and passed through a 2-mm sieve. Soils were analyzed for: nitrate (NO_3-N), ammonium (NH_4-N), total N (TN), total C (TC), C:N ratio, and total soluble polyphenolics (TSP). Soil inorganic N content was determined using Lachet QuickChem Methods. A LECO TruSpec CN analyzer (LECO Corp., St. Joseph, MI) was used to determine TC, TN and the C:N ratio. Total soluble polyphenolic content was determined using the Folin-Ciocalteau technique (Suominen and others 2003). For this analysis, soil extracts (2 ml) were mixed with 2 ml distilled water, 5 ml Na_2CO_3 (20 percent) and 1 ml Folin-Ciocalteau reagent (Sigma-Aldrich); this mixture was incubated for 30 minutes to allow for color development. Tannic acid was used as the standard and absorbance was read at 735 nm.

Vegetation Sampling

Vegetation sampling occurred in July 2006; a mid-season date was chosen to allow the capture of the greatest understory richness with a single sampling event. At each 1-m^2 quadrat, all herbaceous vegetation rooted within the quadrat was identified to species where possible and percent cover was estimated. Woody vegetation < 1 m in height within the quadrat was identified to species and number of stems tallied.

Data Analysis

Correlation analysis was used to determine associations between the soil chemical characteristics (NO_3-N, NH_4-N, TN, TC, C:N ratio, and TSP), the understory vegetation characteristics (herbaceous percent cover or number of woody stems) and the topographical characteristics (planform, FA, slope, and elevation). Regression analysis was used to determine if any of the soil chemical parameters could explain the variation observed in understory vegetation characteristics. Likewise, regression analysis was used to determine if topographical characteristics could explain the variation in soil chemical parameters or in understory vegetation characteristics. Log transformations of NO_3-N, NH_4-N, flow accumulation, and slope were used in these analyses due to non-normal distributions of these data parameters. All statistical analyses were performed using SAS 9.1 (SAS Institute Inc., Cary, NC, 2002-2003).

RESULTS

Floodplain Characteristics

Yellow Creek

Topographical evaluation of the Yellow Creek plots revealed a flat terrain. At plot 1, the elevation gradually decreased as distance from the river increased; the change in elevation across the plot was a total of 0.35 cm (Fig. 2A). Change in elevation at plot 2 was more subtle, with a difference of only 0.15 cm across the plot. This plot did not exhibit the same trend in elevation observed at other plots, as elevation increased as distance from river increased (Fig. 2B).

Planform analysis for plot 1 revealed concave areas associated with the 30-m parallel transect line (quadrats B2, C2, and D2) and parts of the 50-m parallel transect line, particularly near quadrats A4 and D4. Planform features for plot 2 closely mimicked elevation changes. In plot 2, the 20-m parallel transect showed a concave planform; this area of concavity extended diagonally across the plot, and corresponded to areas designated as having lower elevations, such as quadrats C2 and C3. One small area, near quadrat A2, showed a convex character.

In plot 1, the greatest FA was associated with quadrat A4 (FA = 169.0). Other quadrats with high FA included B3 (FA = 41.8), B2 (FA = 28.0), and C2 (FA = 24.9). Slope was minimal across the plot, with the

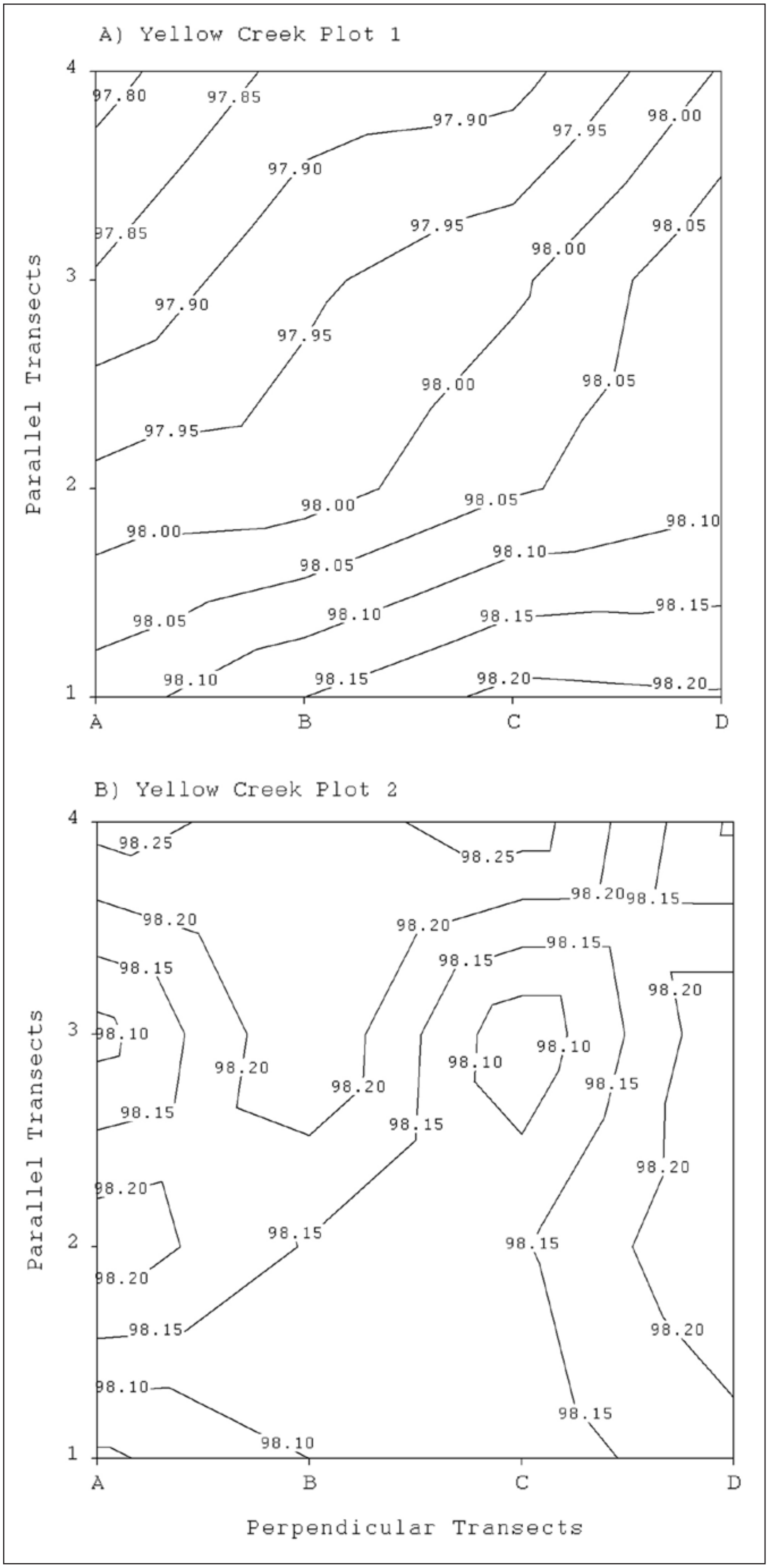

Figure 2.—Elevation maps of Yellow Creek Plots: A) Yellow Creek Plot 1, B) Yellow Creek Plot 2. Elevations for each quadrat were taken with standard survey equipment using a reference point of 100 cm. All transect lines are 10 m apart. Parallel transects numbers correspond to position relative to stream bank; i.e. parallel transect 1 is closest to the stream (20 m distance from stream bank) while parallel transect 4 is farthest from the stream (50 m distance from stream bank).

highest slopes observed at quadrats B3 and C1 (slope = 0.023° for both). In plot 2, FA varied little across the landscape. Quadrats C2 and D4 each had an FA of 10.0; all other quadrats had an FA of 5.0. Again, slope was minimal with the highest slopes recorded in quadrats A4, C4, and D4 (slope = 0.04 degrees for each).

Locust Creek

As with the Yellow Creek plots, elevation differences across the floodplains were minimal for the Locust Creek sites. Locust Creek plot 1 showed a similar pattern to Yellow Creek plot 1, with elevation gradually decreasing in a diagonal fashion across the plot from a "high" at quadrat D1 to a "low" at quadrat A4 (Fig. 3A). Similarly, Locust Creek plot 2 had highest elevation at the 20-m parallel transect line, and a gradual decrease in elevation with increased distance from the river (Fig. 3B). The total elevation gradients for plots 1 and 2 were 0.30 cm and 0.20 cm, respectively.

Planform analysis for Locust Creek plot 1 revealed a gently rolling topography. Concave features were found at or near quadrats B1, C3, and A4, while convex features were found at or near quadrats D1, C2, and D4. Locust Creek plot 2 was notable in its lack of variation; one convex feature of note was located near quadrat A4. Two potential concave features were observed near quadrats C2 and C4.

Flow accumulation in plot 1 was greatest in quadrat B2 (FA = 79.7). Other quadrats with high FA included B3 (FA = 43.6) and B4 (FA = 30.1). In plot 1, slope was greatest in quadrats A3 (slope = 0.95 degrees) and C2 (slope = 0.92 degrees). Quadrats D3, C1, and A2 also had high slopes (slope = 0.86 degrees, 0.74 degrees, and 0.73 degrees respectively). Flow accumulation was generally lower in plot 2 than in plot 1, with the highest FA observed in quadrat C4 (FA = 43.7) and the second highest FA observed in quadrat C2 (FA = 22.05). The highest slope in plot 2 was observed in quadrat C4 (slope = 1.3 degrees). Slope was also high in quadrats A3 (slope = 0.9 degrees), C3 (slope = 0.8 degrees) and B3 (slope = 0.7 degrees).

Thompson River

Elevation patterns at Thompson River plot 1 resembled those at Yellow Creek plot 1 and Locust Creek plot 1, in that elevation gradually decreased as distance from river increased (Fig. 4A). Again, the gradient was minimal, with a 0.30-cm change in elevation across the floodplain. Thompson River plot 2 showed little variation in elevation, having only a 0.15-cm change in elevation across the floodplain and relatively large areas with no changes in elevation (Fig. 4B).

Planform analysis for Thompson River plot 1 indicated that this plot was centered on a relatively featureless portion of the floodplain. Two small convex areas were apparent at quadrats A3 and D3 of this plot, while concave areas occurred at quadrats B1 and C1; the landscape changed little over the rest of the plot. Plot 2 seems to have more variation in landforms. Two small concave areas were observed at quadrats C2 and D3. Convex features were observed at quadrats C1, D2, and D4, with an almost ridge-like feature extending from quadrat B2 to B3.

The Thompson River plots showed little variation in FA. In plot 1, the greatest FA was recorded in quadrats B4 (FA = 33.5), B3 (FA = 13.5), and A4 (FA = 8.1). In plot 2, quadrats C3 (FA = 12.3) and B4 (FA = 10) had the greatest FA. All other quadrats in both plots had FA = 5.0. The highest slopes overall were recorded in Thompson River plot 1. Quadrats A3 (slope = 2.4 degrees), C2 (slope = 2.2 degrees), and A4 (slope = 2.1 degrees) were the steepest. Other quadrats in plot 1 with high slopes were B3 (slope = 1.8

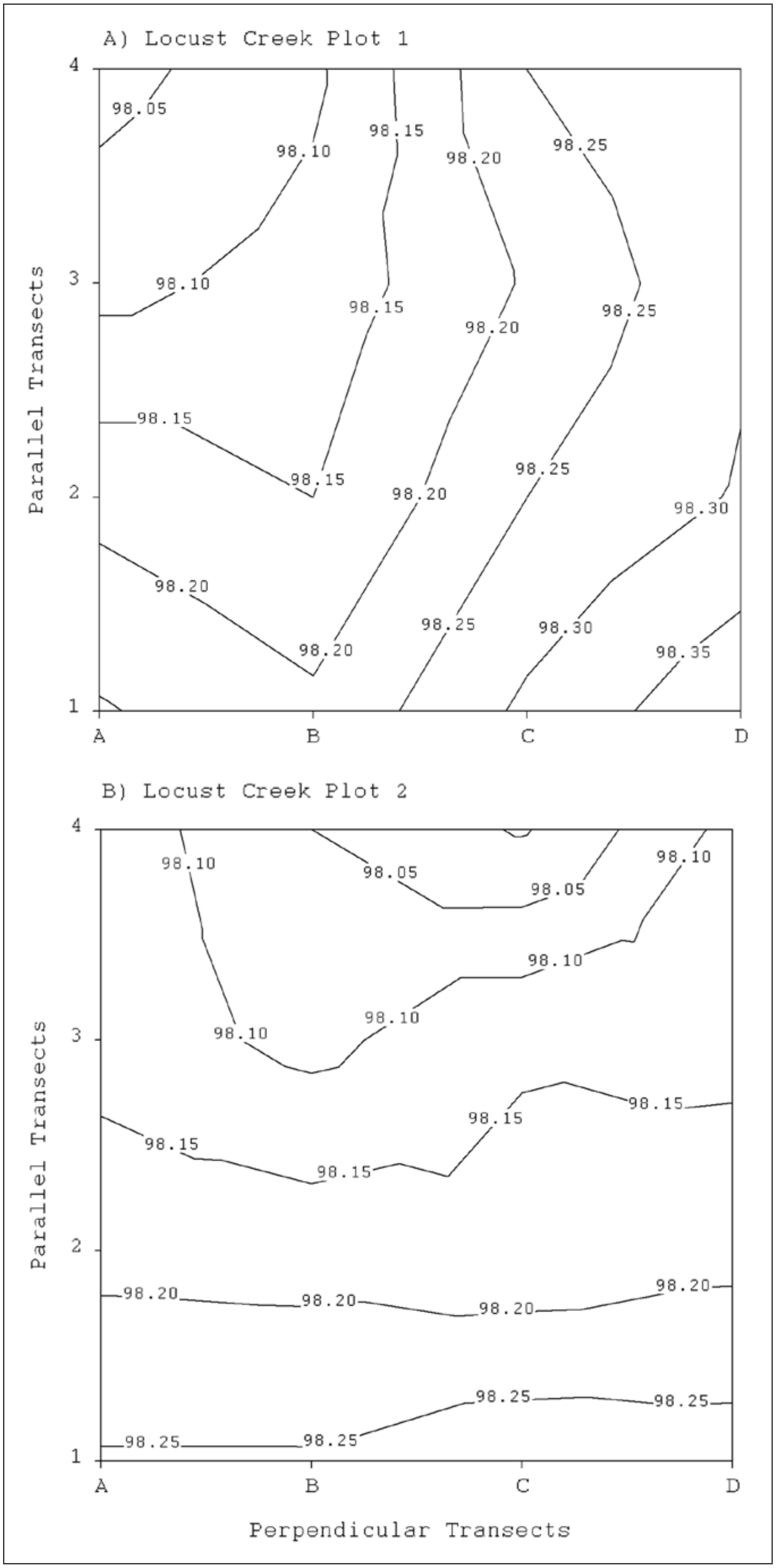

Figure 3.—Elevation maps of Locust Creek plots: A) Locust Creek plot 1; B) Locust Creek plot 2. Elevations for each quadrat were taken with standard survey equipment using a reference point of 100 cm. All transect lines are 10 m apart. Parallel transect numbers correspond to position relative to stream bank; parallel transect 1 is closest to the stream (20 m from stream bank) while parallel transect 4 is farthest from the stream (50 m from stream bank).

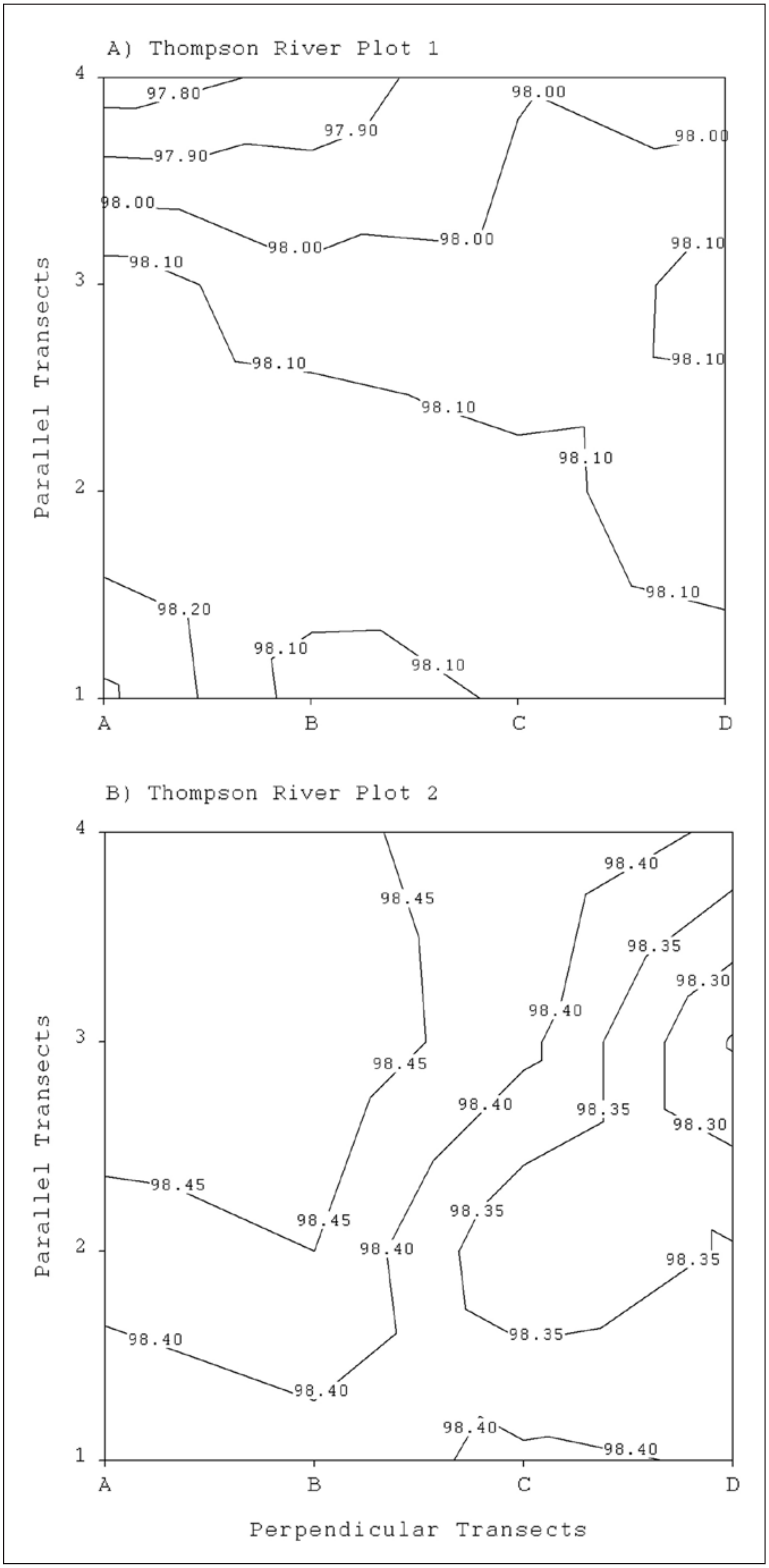

Figure 4.—Elevation maps of Thompson River plots: A) Thompson River plot 1; B) Thompson River plot 2. Elevations for each quadrat were taken with standard survey equipment using a reference point of 100 cm. All transect lines are 10 m apart. Parallel transect numbers correspond to position relative to stream bank; parallel transect 1 is closest to the stream (20 m from stream bank) while parallel transect 4 is farthest from the stream (50 m from stream bank).

degrees) and C3 (slope = 1.7 degrees). In plot 2, quadrat D4 had the greatest slope (slope = 1.1 degrees), followed by quadrat C3 (slope = 1.0 degrees). Other quadrats with high slopes included C1, A3, and B1 (slopes = 0.8 degrees, 0.8 degrees, and 0.7 degrees, respectively).

Soil Chemistry and Vegetation

Soil Chemistry

Differences between sites and plots within sites were observed for NO_3-N, TC, TN, and TSP. Overall, Locust Creek soils had the highest levels of NO_3-N and the lowest levels of TC, TN, and TSP. Yellow Creek soils had the highest levels of TC and TN while Thompson River had the highest levels of TSP (Appendix 1). Plot-level differences in NO_3-N were observed at the Thompson River sites and within-plot differences were observed at Yellow Creek plot 2 and Locust Creek plot 2. Plot-level differences in TC and TN were observed at Locust Creek, with plot 2 having lower levels of both variables. Yellow Creek plot 2 showed increasing TN with distance from river; no other within-plot differences were observed for TC and TN. There were no plot-level differences observed for TSP levels; however, within-plot differences were observed at Thompson River plot 2. Finally, differences in NH_4-N and C:N were not detected at any level of comparison.

Understory Characteristics

Understory vegetation was measured in two ways: percent cover of herbaceous species and number of stems of woody shrubs and vines. The three study sites differed for both of these characterizations. Overall, Locust Creek had significantly greater percent cover of herbaceous vegetation than Thompson River. (Yellow Creek had intermediate herbaceous coverage.) On the other hand, the shrub layer at Locust Creek was nearly absent while the Yellow Creek shrub layer density was so great as to impede movement through the stand. No trends between understory vegetation and distance from river were observed. Herbaceous coverage did not increase, nor were any differences in number of woody stems observed as distance from river increased although both parameters varied from line to line at each plot. See Appendix 2 for a list of the most common understory species in each plot. Herbaceous species differences from detected at the creek level and for all plots except the Yellow Creek plots. These differences can be attributed primarily to *Laportea canadensis* and *Parthenocissus quinquefolia*, which had the highest overall cover values and were significantly different than most other species. Species differences were also observed in the shrub layer; *Toxicodendron radicans* had the highest number of stems and was significantly different from most other species. *Toxicodendron radicans* was particularly dense at Yellow Creek and contributed to the high number of woody stems observed at those plots.

Overstory Characteristics

The overstory vegetation was not significantly different among sites when compared in terms of basal area (BA), relative dominance, relative density, or importance values. However, a disproportionate dominance by a single species was observed in most plots (Appendix 2). Yellow Creek plot 1 was dominated by *Acer saccharinum*, while Yellow Creek plot 2 was dominated by *Quercus macrocarpa*. *Acer saccharinum* dominated both plots at Locust Creek. The dominant species at Thompson River plot 1 was *Celtis occidentalis*, while at Thompson River plot 2, dominance was shared between *Platanus occidentalis* and *Ulmus americana*. Thompson River plot 2 had a high number of small-diameter *Ulmus americana*, a notable difference from other plots.

Correlation of Soil, Vegetation, and Microtopography

Correlation analysis of soil parameters indicated positive correlations between TC and TN ($r = 0.96$, $P < 0.0001$), and TC and C:N ratio($r = 0.27$, $P = 0.01$). Soil TSP content was positively correlated with TC (r = 0.46, P <0.0001) and TN (r = 0.42, P <0.0001). No other correlations were detected among soil chemical parameters.

Herbaceous cover was negatively correlated with number of woody stems (r = -0.66, P <0.001), TC (r = -0.50, P < 0.0001), and TN (r = -0.53, P <0.0001). Conversely, number of woody stems was positively correlated with TC (r = 0.60, P < 0.0001) and TN (r = 0.64, P <0.0001). No correlations were observed between the soil chemical parameters NO_3-N, NH_4-N, or TSP and vegetation variables.

There were no significant correlations among the microtopographical variables (planform, flow accumulation, slope, and elevation). Slope, however, was positively correlated with NO_3-N (r = 0.28, P <0.01) and negatively correlated with NH_4-N (r = -0.24, P = 0.03), TN (r = -0.61, P <0.0001), and TC (r = -0.60, P <0.0001). Elevation was negatively correlated with NO_3-N (r = -0.24, P = 0.02), TN (r = -0.33, P < 0.002), and TC (r = -0.38, P <0.001). No other correlations between microtopography and soil chemical parameters were observed. Herbaceous cover was positively correlated with flow accumulation (r = 0.34, P <0.002) and slope (r = 0.50, P <0.0001). Meanwhile, number of woody stems was negatively correlated with slope (r = -0.61, P <0.0001) and elevation (r = -0.26, P <0.02).

Regression Analyses

Regression analyses showed that slope and elevation could explain some of the variation observed in soil chemistry. Specifically, these two microtopographical variables could explain 15 percent of the variation observed in NO_3-N (P < 0.001), and 41 percent of the variation observed in both TC (P < 0.0001) and TN (P < 0.0001). Models that would adequately explain variation in NH_4-N, C:N ratio, or TSP were not observed. Significant relationships are represented by the following regression equations:

NO_3-N = 44.49 + 0.10 (slope) - 0.45 (elevation)
TC = 117.79 - 0.48 (slope) - 1.18 (elevation)
TN = 7.77 - 0.04 (slope) -0.08 (elevation)

Variation in herbaceous cover and number of woody stems could also be explained by microtopographical variables. In the case of these understory vegetation parameters, however, FA and slope were the most important microtopographical factors. Flow accumulation and slope can be used to explain approximately 38 percent of the variation observed in herbaceous cover (P <0.0001) and approximately 40 percent of the variation observed in number of woody stems (P <0.0001). These relationships are represented by the following regression equations:

herbaceous cover = 63.43 + 49.06 (FA) + 31.89 (slope)
number of woody stems = 3.07 - 2.95 (FA) - 3.97 (slope)

Variation in understory vegetation parameters could also be explained by soil chemistry. In this case, variation observed in herbaceous cover as well as in number of woody stems was best explained by TN content of the soil. TN could be used to explain 28 percent of the variation observed in herbaceous cover (P <0.0001), and 41 percent of the variation observed in number of woody stems (P <0.0001). The relationships between TN and these understory vegetation parameters are represented by the following regression equations:

herbaceous cover = 160.93 - 444.25 (TN)
number of woody stems = -6.82 + 56.95 (TN)

DISCUSSION

Unlike riparian forests in the Ozarks (Becker 1999, Lyon and Sagers 1998, Sagers and Lyon 1997), such forests in the river hills of northwestern Missouri showed little topographical relief. These distinctions are expected with landscapes that differ in glacial history and geological processes. Our study areas were located in a section of the Central Dissected Till Plains characterized by broad valley bottoms and smooth uplands with less than 30 m of relief (Nigh and Schroeder 2002). Thus, when we used distance from river as a proxy for flood frequency (and assumed that locations closest to the river would flood more frequently), we were unable to find relationships between flood frequency and levels of inorganic N or TSP in the soil.

Microtopographical variations can be expected even on apparently featureless landscapes. Measures such as elevation, planform, flow accumulation, and slope should give an indication of places in the landscape where water might be expected to accumulate and thus affect soil nutrient cycling and vegetative occurrence and growth. For example, areas of higher elevation would experience less accumulation of water and sediments. Likewise, areas with greater slope would experience more movement of water away from the area. On the other hand, areas with lower elevation, less slope, or concave features would experience greater accumulations of water and dissolved substances. In these areas one might expect to observe greater concentrations of soil chemicals, including inorganic N, C, and TSP. We observed a positive correlation between slope and NO_3-N and negative correlations between slope and NH_4-N, TN, and TC. Therefore, in areas with steeper slopes, we observed higher concentrations of NO_3-N and lower concentrations of NH_4-N, TN, and TC. We also observed a negative relationship between elevation and NO_3-N, TN, and TC, which would indicate that higher positions in the landscape had lower concentrations of these soil chemical parameters. While the effects of slope and elevation on NO_3-N are opposite, they are in agreement for TC and TN. Total C and TN concentrations seem to increase along a gradient from higher elevation to lower elevation, with the greatest reduction in TC and TN corresponding to the areas with the greatest changes in elevation (i.e., highest slope).

Despite observing only slight changes in elevation across our sites, we found correlations between site variables and elevation. In addition to the correlations with soil chemical variables discussed above, elevation was negatively correlated with number of woody stems. These results are similar to other studies where elevation was found to be the primary determinant of site characteristics (Grell and others 2005, Lyon and Sagers 1998, Turner and others 2004). For example, in a study of old-growth bottomland hardwood-loblolly pine forests in southern Arkansas, Grell and others (2005) found elevation to be correlated with 75 percent of the environmental variables measured. Likewise, importance values for 35 percent of seedling species, 30 percent of overstory species, 22 percent of herbaceous species and 8 percent of sapling species differed significantly by elevation class in this study (Grell and others 2005). In a comparison between upland and floodplain sites, Holmes and others (2005) found that percent TN as well as concentrations of NO_3-N, P, K, Ca, Mg, Mn, and Zn were all significantly higher on floodplain landforms than upland landforms. In addition, these landforms differed in groundflora composition as well as in soil organic matter, pH, and texture (Holmes and others 2005). While Grell and others (2005) and Holmes and others (2005) made comparisons on a more coarse scale, Beatty (1984) considered microtopographical effects of forest floor treefall mounds and pits on soil nutrient levels within a maple-beech forest. In this study, the mounds were found to be of poorer nutrient content and to have less organic matter than the pits (Beatty 1984). This finding is in agreement with the observation that areas higher in elevation in the studied riparian forest floodplains (similar to the mounds in Beatty [1984]) had lower concentrations of TN and TC.

Since we analyzed the effects of soil chemistry and microtopography on understory vegetation separately, it is not clear which variables are acting as the dominant structuring agents. Further, the herbaceous and shrub layers not only respond differently to these parameters, but they are also negatively correlated with each other. Therefore, it is not known if they are responding to each other or to gradients in soil chemistry or microtopography or possibly to the overstory. For example, herbaceous cover and number of woody stems are both correlated with TN; however, herbaceous cover is negatively correlated with TN while number of woody stems is positively correlated with TN. It is possible that the shrubs are out-competing the herbaceous plants on the microsites with greater TN, relegating the herbaceous plants to microsites with lower TN. On the other hand, herbaceous plants might be better able to tolerate lower TN and are therefore found on these microsites preferentially.

The herbaceous and shrub layers also responded differently to microtopographical variation. Herbaceous cover was positively correlated with flow accumulation and slope, while number of woody stems was negatively correlated with slope and elevation. Likewise, regression analysis showed a positive relationship between the herbaceous layer and flow accumulation and slope and a negative relationship between the shrub layer and these variables. If we relate these microtopographical observations to expected effects on water movement and accumulation on the landscape, herbaceous cover prevailed in wetter areas and and woody species in drier areas. These findings yet beg the question: are the herbaceous species better competitors for the more moist positions in the landscape or are woody species somehow more tolerant of drier conditions?

Differential response of forest layers to environmental gradients has been observed in other studies (Grell and others 2005, Lyon and Gross 2005, Lyon and Sagers 1998, Lyon and Sagers 2002, Sagers and Lyon 1997), in which site heterogeneity was hypothesized as the cause for this uncoupling. For example, Lyon and Gross (2005) observed four distinct assemblages of overstory species that responded to soil and topography characteristics; however, no distinct shrub assemblages were identified and shrubs were not correlated with environmental parameters. Lyon and Sagers (1998) failed to find any significant coupling between tree and herbaceous layer assemblages. Vegetation layers certainly respond to environmental gradients, but layers may respond differentially to such gradients (Sagers and Lyon 1997). In the current study it may be possible that the shrub layer is responding to variations in microtopography and/or soil nutrients and thereby competing with the herbaceous community.

The results of the current study suggest the importance of microtopography for floodplain restoration efforts. The floodplains in this study appeared quite uniform at first glance; however, differences in soil chemistry across the floodplains became apparent when microtopographical measures were taken into account. While not measured directly, differences in soil moisture may also be assumed; water would be expected to accumulate at lower elevation points or in convex landscape features. Other studies have documented the need for considering microtopographical influences along with flood tolerance ratings during floodplain restoration efforts. Grell and others (2005) recommend flood-tolerant species on areas that experience annual flooding and moderately tolerant to intolerant species on higher sites that rarely flood. Likewise, McLeod and others (2000) noted differential survival due to planting elevation; flood-tolerant species had greatest survival in lowest elevation sites and flood-intolerant species had greatest survival in relatively drier sites. Restoration plans should, therefore, include a fine-scale evaluation of elevation contours and species selection based on relative flood tolerance.

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Appendix 1.--Soil chemical characteristics of study plots. Ave. = average value of the chemical variable for the plot; min. = minimum quadrat value recorded at that plot; max. = maximum quadrat value recorded at that plot. TC = total carbon, TN = total nitrogen, and TSP = total soluble polyphenolics.

	NH_4-N (ppm)	NO_3-N (ppm)	TC (%)	TN (%)	C:N Ratio	TSP (ppm)
Yellow 1						
Ave.	6.07	1.09	2.86	0.24	11.60	10.75
Min.	3.32	0.52	2.06	0.19	10.28	4.63
Max.	8.82	3.03	4.13	0.32	13.16	14.75
Yellow 2						
Ave.	6.20	0.89	2.71	0.24	11.13	9.83
Min.	0.67	0.47	2.06	0.20	10.37	6.02
Max.	9.39	1.69	3.37	0.29	12.54	16.83
Locust 1						
Ave.	5.03	1.63	1.75	0.15	11.51	9.76
Min.	2.78	0.70	1.35	0.11	10.29	5.82
Max.	8.95	4.82	2.86	0.21	13.46	14.89
Locust 2						
Ave.	5.50	1.23	1.27	0.11	11.74	7.57
Min.	2.44	0.72	0.94	0.08	10.51	4.75
Max.	24.13	3.87	1.56	0.14	15.08	12.26
Thompson 1						
Ave.	4.07	1.88	1.96	0.17	11.38	10.85
Min.	1.07	0.96	0.87	0.07	10.20	7.02
Max.	11.22	2.77	3.41	0.26	12.92	12.26
Thompson 2						
Ave.	6.87	0.60	1.77	0.16	10.90	10.20
Min.	2.70	0.38	1.35	0.12	7.49	6.25
Max.	25.83	0.74	2.05	0.24	12.20	12.60

Appendix 2.—Vegetation characteristics of study plots. Listed are the five most common understory species as determined by cover values and the five most common overstory species based on basal area (m^2 ha^{-1}). Understory species are listed in order from highest to lowest percent cover.

Plot	Understory species	Overstory species	BA (m^2/ha)
Yellow 1	*Boehmeria cylindrica*	*Acer saccharinum*	15.96
	Aster sp.	*Quercus palustris*	7.13
	Viola sp.	*Fraxinus pennsylvanica*	3.19
	Carex squarrosa	*Ulmus rubra*	1.50
	Elymus virginicus	*Carya laciniosa*	1.15
Yellow 2	*Chasmanthium latifolium*	*Quercus macrocarpa*	15.55
	Viola sp.	*Carya laciniosa*	5.73
	Boehmeria cylindrica	*Fraxinus pennsylvanica*	3.68
	Carex muskingumensis	*Celtis occidentalis*	3.62
	Menispermum canadense	*Quercus palustris*	3.35
Locust 1	*Laportea canadensis*	*Acer saccharinum*	33.20
	Parthenocissus quinquefolia	*Platanus occidentalis*	7.40
	Elymus virginicus	*Populus deltoides*	5.71
	Zizia aurea	*Ulmus americana*	3.04
	Poa pratens	*Celtis occidentalis*	1.93
Locust 2	*Laportea canadensis*	*Acer saccharinum*	14.51
	Parthenocissus quinquefolia	*Acer negundo*	11.91
	Rudbeckia lacinata	*Platanus occidentalis*	8.77
	Elymus virginicus	*Populus deltoides*	5.54
	Viola sp.	*Celtis occidentalis*	2.35
Thompson 1	*Laportea canadensis*	*Celtis occidentalis*	18.66
	Viola sp.	*Fraxinus pennsylvanica*	4.66
	Elymus virginicus	*Juglans nigra*	2.28
	Gratiola neglecta	*Quercus macrocarpa*	1.59
	unknown grass	*Carya laciniosa*	1.28
Thompson 2	*Parthenocissus quinquefolia*	*Platanus occidentalis*	12.00
	Laportea canadensis	*Ulmus americana*	10.06
	Amphicarpaea bracteata	*Juglans nigra*	4.06
	Zizia aurea	*Celtis occidentalis*	0.76
	Elymus virginicus	*Morus rubra*	0.47

GROWTH AND FOLIAR NITROGEN CONCENTRATIONS OF INTERPLANTED NATIVE WOODY LEGUMES AND PECAN

J.W. Van Sambeek, Nadia E. Navarrete-Tindall, and Kenneth L. Hunt[1]

Abstract.—The interplanting and underplanting of nodulated nitrogen-fixing plants in tree plantings can increase early growth and foliage nitrogen content of hardwoods, especially black walnut and pecan. Recent studies have demonstrated that some non-nodulated woody legumes may be capable of fixing significant levels of atmospheric nitrogen. The following nine nurse crop treatments were established with and without interplanted northern pecan: the nodulated legumes black locust, false indigo, and smooth false indigo; non-nodulated thornless honeylocust, Kentucky coffeetree, and redbud; non-leguminous buttonbush; 16N-8P-8K tree food spikes; and a control without shrubs or fertilizer. Average foliage nitrogen content of the nurse trees ranged from 3.3 percent for black locust, false wild indigo, and smooth wild indigo, and 2.1 percent for honeylocust and Kentucky coffeetree, to 1.8 percent for redbud and buttonbush. In the fourth growing season, pecan foliage nitrogen was similar across all treatments (1.8 to 2.0 percent); however, black locust had increased pecan foliage nitrogen to 2.2 percent in the sixth growing season. Pecan growth is similar across all treatments except when interplanted with black locust that overtopped the pecan and is suppressing its growth. Interpretations include the possibilities that soil nitrogen was adequate to preclude any benefits from biologically fixed nitrogen, that nurse plants did not release sufficient fixed nitrogen to increase pecan growth, and foliage nitrogen in non-suppressed saplings, or that other soil factors are limiting pecan development.

INTRODUCTION

The interplanting of nodulated nitrogen-fixing woody shrubs and trees into hardwood plantings can substantially increase hardwood tree growth (Plass 1977, Hansen and Dawson 1982, Schlesinger and Williams 1984, Dawson and Van Sambeek 1993). Nodulated nitrogen-fixing woody plants can include species that form symbiotic associations with either actinomycetes (actinorhizal plants) or rhizobial bacteria (legumes). On low-nitrogen sites, nitrogen-fixing plants can obtain up to 70 percent of their nitrogen through fixation within root nodules (Tripp and others 1979). Some of this nitrogen can become available to adjacent non-nitrogen-fixing plants through root exudates or decomposition in soil of leaves and roots (Friedrich and Dawson 1984, Avery 1991, Dawson and others 1992).

Much of the early research on interplanting nitrogen-fixing woody plants in the Central Hardwood region has been done with non-native actinorhizal shrubs and trees. Species have included autumn olive (*Elaeagnus umbellata* Thunb.), Russian olive (*E. augustifolia* L.), and European black alder (*Alnus glutinosa* (L.) Gaertn.)(Schlesinger and Williams 1984, Van Sambeek and others 1985). Black locust (*Robinia pseudoacacia* L.) has been the most promising nodulated temperate woody legume (Haines 1978). Estimates of the annual nitrogen input within black locust stands range from 30 to 56 kg ha^{-1} (Ike and Stone 1958, Boring and Swank 1984).

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Most of the woody legume species found in the Central Hardwood region are included within the Caesalpinioideae subfamily of the Fabaceae. More than 70 percent of the legumes classified within this subfamily are not nodulated and were thought not to have the ability to fix atmospheric nitrogen (Allen and Allen 1981, De Faria and others 1989). Bryan and others (1996) examined 12 non-nodulated tree legumes to evaluate their nitrogen-fixing capacity. They found rhizobial bacterioids within roots of six species, including honeylocust (*Gleditsia triacanthos* L.), and reported all species had nitrogenase activity which indicated the capacity to fix nitrogen although fixation rates were 1- to 2-fold lower than for nodulated tree legumes. Navarrete-Tindall and others (1996) have also reported acetylene-reduction activity from honeylocust seedlings when inoculated with one of four rhizobial strains isolated from a tropical woody legume.

OBJECTIVES

The objectives of our study were 1) to determine if non-nodulated native woody legumes produce foliage high in nitrogen; and 2) to determine if native woody legumes established as nurse crops can improve foliage nitrogen content and growth of interplanted northern pecan.

MATERIAL AND METHODS

The study was established on a 0.7-ha old-field site inside a 2-m-high, 6-strand electric fence at the Horticulture and Agroforestry Research Center (New Franklin, MO). The site is along a south-facing toe-slope with Memfro silt loams. The area was repeatedly tilled in spring 2001 before laying out twenty-four 42-m-long rows 4.5 m apart. Odd-numbered rows were planted to pecans (*Carya illinoensis* (Wang.) K. Koch) 3 m apart alternating between 1-0 bareroot stock from Forrest Keeling Nursery (Elsberry, MO) and 2-year-old grafts. Scionwood of Peruque, Kanza, or Posey were spring grafted in 1999 to 1-0 bareroot pecan rootstocks from Cascade Forestry Nursery (Cascade, IA) planted in 25-cm-tall 12-L plastic pots. Circling roots on the container-grown pecan grafts were cut before field planting. Because of the long taproots, both the bareroot stock and grafts were planted with tile spades in early May 2001. A 60-cm-long perforated semi-transparent tree shelter was placed over each grafted pecan after planting and removed in spring 2005.

Each row was divided into three 12-m-long treatment plots separated by 3-m-long border plots. The nine nurse crop treatments randomly assigned to the three odd-numbered rows within each block were interplanting with the nodulated legumes black locust (*Robinia pseudoacacia* L.), false indigo (*Amorpha fruticosa* L.), and smooth false indigo (*A. nitens* Boynton); the non-nodulated legumes thornless honeylocust (*Gleditsia triacanthos* var. inermis), redbud (*Cercis canadensis* L.), and Kentucky coffeetree (*Gymnocladus dioicus* (L.) K. Koch); the non-leguminous buttonbush (*Cephalanthus occidentalis* L.); slow-release 16N-8P-8K fertilizer spikes; or control without nurse plants or fertilizer. Within the odd-numbered rows, two nurse crop seedlings were planted within the tree row at a distance of 1 m on either side of each pecan seedling or grafted sapling. The same nine treatments were randomly assigned to the three even-numbered rows within each block. In these treatment plots, a plant of the same species as the nurse crop treatment was planted as the crop tree instead of a pecan.

Pecan and all nurse crop treatments except buttonbush were established in spring 2001. Bareroot 1-0 nursery of black locust and redbud seedlings were obtained from Forrest Keeling Nursery and planted with KBC planting bars. Kentucky coffeetree seed collected in southern Illinois were direct-seeded with two seeds in each planting spot in spring 2001. If seed failed to germinate, 1-0 nursery stock was added to planting spot in spring 2002. False indigo and smooth false indigo seedlings were grown from seed collected in southern Illinois (Taft 1994). Seed was sown in flats in the campus greenhouse and germinates transplanted to 0.5-L pots. Seedlings were inoculated and than transplanted as in-leaf stock. Honeylocust seedlings were planted as 3-0 in-leaf container-grown stock grown from seed collected from two thornless honeylocust trees. Because many of the seedlings developed thorns, only one seedling was available for planting within 1 m of a crop tree. Annually from 2001 through 2005, a 16N-8P-8K Jobe's tree food spike (Easy Gardener, Ltd., Waco, TX) was hammered 5 cm deep below soil line within the tree row at a distance of 1 m on either side of each pecan.

Each 12-m long treatment plot was divided in half and one of two weed control treatments randomly assigned to each subplot. One subplot was chemically treated each spring with a combination of glyphosate (6.4 L ha^{-1}) and simizine (4 kg ha^{-1}) for 2 years. For the other subplot, two 6-m-long strips of 1.2-m-wide woven polypropylene fabric were placed along the tree row, cut to make 20-cm long slits by each tree, and then overlapped within tree row before pinning down the center was pinned down and the edges buried. Quizalofop (77 g ha^{-1}) was sprayed in July 2001 and fluazifop (1.4 kg ha^{-1}) was sprayed over the top in May 2002 to control invading grasses within all tree rows. Alleys between tree rows were mowed periodically with a side discharge mower, allowing plant residues to cover the black weed barrier. In spring 2003, alleys between rows were disked and allowed to revegetate. All nurse crop trees were coppiced in late spring 2005, stems shredded, and residue placed back within the same tree row. The crop trees for both the pecan and nurse crop species have been annually pruned since 2004 to develop a single dominant stem with approximately 40 percent clear bole.

Crop and nurse trees were measured for height and basal diameter of largest stem and total number of vertical stems in the lower 30 cm in fall 2001, 2002, 2003, 2004, and 2006. In addition, if fruits were present, the approximate number of fruits or racemes was recorded in fall 2003, 2004, and 2006. Leaves, including the petioles, were collected from the center of the new growth from each crop tree in late July 2004 and late July 2006. Leaves of all crop trees within a treatment plot were combined, oven-dried at 60 °C, and ground to pass a 1-mm screen. Foliage samples were analyzed for total nitrogen by infrared spectrometry.

Treatment means for crop tree responses were subjected to analysis of variance for a split-plot design with four replications of nurse crop treatments as the main plot and methods of weed control and/or stock types as subplots. Separate analyses were done for the odd-numbered rows containing pecans as crop trees and for the even-numbered rows with nurse crop trees as the crop trees.

RESULTS

Foliage nitrogen content of the nurse crop trees ranged from 1.7 to 3.4 percent and separated into three distinct groups in both the 2004 and 2006 growing seasons (Table 1). Black locust, false indigo, and smooth false indigo are in the high foliage-nitrogen group, with foliage nitrogen ranging from 3.1 to 3.4 percent. Foliage nitrogen concentrations for black locust are within the range reported by Hacskaylo and others (1969) for seedlings grown with a complete nutrient solution or in solutions lacking a single essential mineral except nitrogen. Kentucky coffee tree and honeylocust were in an intermediate group with foliage nitrogen concentrations ranging from 2.1 to 2.6 percent. For these two species, foliage nitrogen was higher in the 2004 than in the 2006 growing season. Redbud and buttonbush were in the lowest group, with foliage nitrogen concentrations ranging from 1.7 to 1.9 percent.

Table 1.—Foliage nitrogen concentration of pecan and nurse trees in late July of fourth (2004) and sixth (2006) growing seasons

	Pecan foliage nitrogen (%)		Nurse crop foliage nitrogen (%)	
Treatment	July 2004	July 2006	July 2004	July 2006
Black locust	1.97	2.20	3.17	3.35
False indigo	1.85	1.77	3.16	3.25
Smooth false indigo	1.87	1.88	3.23	3.19
Honeylocust	1.93	1.74	2.35	2.02
Kentucky coffeetree	1.86	1.77	2.57	2.27
Redbud	1.97	1.92	1.76	1.84
Fertilizer spikes	1.92	1.78	----	----
Buttonbush	1.88	1.90	1.91	1.88
Control	1.86	1.78	----	----
LSD (p<0.05)	0.18	0.20	0.37	0.26

Table 2.—Survival percentages 2, 4, and 6 years after planting for pecan and nurse crop trees established with either weed barrier strips or chemical weed control

			Survival (%)					
			Weed barrier			Chemical control		
Tree species	Planting stock type	Number planted	Year 2	Year 4	Year 6	Year 2	Year 4	Year 6
Pecan	1-0 seedlings	72	81	81	81	72	72	72
Pecan	3-0 grafts	72	100	100	100	100	100	97
Black locust	1-0 seedlings	80	68	78	90	78	85	92
False indigo	Germinant	80	98	98	95	90	90	90
Smooth indigo	Germinant	80	90	88	85	65	62	68
Honeylocust	3-0 container	44	100	100	100	100	100	100
Coffeetree	Seed	80	60	78	85	55	85	90
Redbud	1-0 seedlings	80	78	70	68	100	95	95

Nitrogen content of the pecan foliage ranged from 1.8 to 2.0 percent in the fourth growing season with no detected differences among treatments (Table 1). In the sixth growing season, pecan growing with black locust had higher foliage nitrogen than did pecan in any of the other nurse treatments. Foliage nitrogen concentrations of pecan in all plots are below those recommended for optimal growth of pecan (Sparks 1979, Mills and Jones 1996). Analyses of the other foliage macronutrients and micronutrients did not reveal any deficiencies that might explain why pecan foliage nitrogen was not raised by several treatments, especially by the slow-release fertilizer spikes.

Survival across species through the first 6 years was quite variable (Table 2). Survival of the pecan grafts, in-leaf honeylocust, and in-leaf container-grown false indigo has been excellent. Seedlings of pecan and black locust exhibited relatively high initial mortality regardless of type of weed control; however, many of the dead black locust seedlings were replaced by sprouts by year six. The increased survival percentages for Kentucky coffeetree may have resulted from a combination of delayed seed germination and poor survival of replacement nursery stock (Sander 1974). Mortality of smooth false indigo germinants was higher with chemical weed control than with the weed barrier fabric. In contrast, mortality of redbud seedlings was

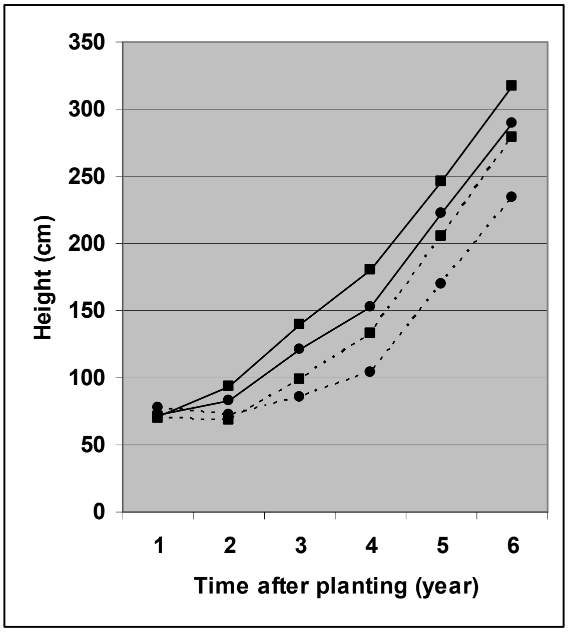

Figure 1.—Height of pecan seedlings (dotted line) and grafts (solid line) with 2 years of chemical weed control (circles) or weed barrier fabric (squares).

Table 3.—Mean sixth-year stem height and basal diameter of surviving pecans interplanted with woody legumes or fertilized with tree spikes

Nurse Crop Treatment	Height --cm--	Diameter --mm--
Fertilizer spikes	323 a	58 a
Kentucky coffeetree	308 a	55 ab
Control	295 a	54 ab
Buttonbush	295 a	52 ab
False indigo	292 a	51 ab
Smooth false indigo	281 a	49 ab
Honeylocust	291 a	48 ab
Redbud	281 a	42 bc
Black locust	183 b	31 c

lower with chemical weed control than with the weed barrier fabrics, suggesting redbud may be sensitive to the high soil temperatures associated with use of black weed barrier fabrics (Van Sambeek and others 1995). No additional mortality occurred between the fourth and sixth year, which suggests all the nurse crop species trees were tolerant of being coppiced in the spring of the fifth year.

Pecans interplanted with the fast-growing black locust were shorter and smaller than pecans in any other nurse crop treatment except for redbud after the sixth growing season (Table 3). By the fourth growing season, black locust had overtopped and slightly reduced stem height but not basal diameter of the pecans, which prompted us to coppice the nurse trees in all treatments the following spring. The grafted pecans planted as container stock with a 3-year-old rootstock grew faster after the second growing season than the pecans planted as bareroot nursery stock (Fig. 1). Both stock types exhibited the initial slow above-ground growth expected with transplanted pecans as they develop deep, large taproots. After the third growing season, pecans established with a 2-m-wide strip of weed barrier fabric grew faster than pecan established with a 2-m-wide herbicide strip (Fig. 1).

Differences in average height of the nurse tree species grown as crop trees were detected after the first growing season (Fig. 2). Unlike with pecan, no statistical differences were found between the two types of weed control in height or diameter of any nurse crop species. The height of honeylocust and redbud saplings most closely matched the height of the pecans. Black locust had very rapid height growth and overtopped the pecan seedlings or grafts even when coppiced. In contrast, initial height growth of Kentucky coffeetree, a common associate of pecan on bottomland sites, was quite slow but shows signs of accelerating now that the saplings are established.

Germinants of false indigo initially grew faster than smooth false indigo the first growing season; however, growth rates declined for both species when they started flowering in the second growing season. Similar

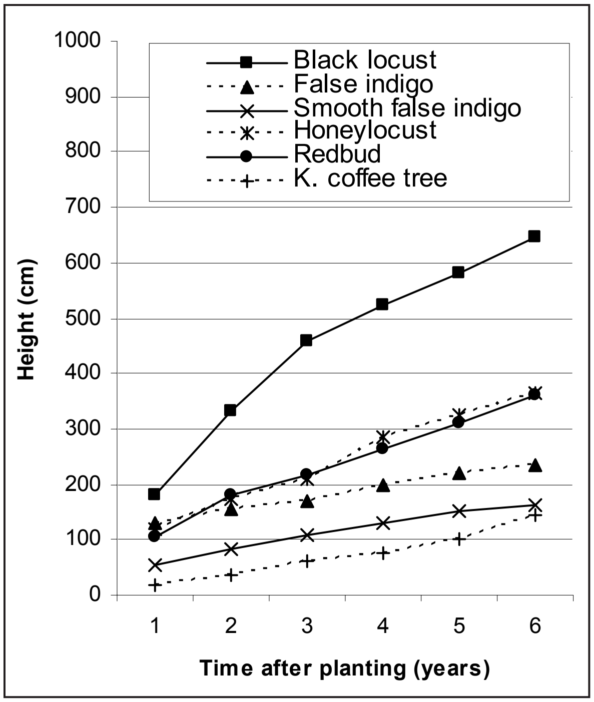

Figure 2.—Height of nurse crop trees and shrubs grown as noncoppiced crop trees within the nurse crop treatments.

differences in growth rate have also been found with stem cuttings (Navarrete-Tindall and others 2002). Although they each have unique morphological characteristics, smooth false indigo, a threatened and endangered species, is sometimes classified as a subspecies of false indigo (Wilbur 1975). False indigo has cuspidate leaflets with a sharp tip at the apical end, and the new shoots originating from buds basal to the flowering spikes tend to elongate past and hide the developing fruit. In contrast, smooth false indigo has emarginated leaflets with a slight indentation at the tip, and new shoots with fewer and smaller leaves leave developing fruit visible.

DISCUSSION AND CONCLUSIONS

The foliage nitrogen concentrations of the nurse crop species tended to follow the pattern suggested by McKey (1994) and Bryan and others (1996). The nodulated legumes had the highest percent nitrogen, non-nodulating legumes had intermediate levels, and the nonleguminous plants the lowest levels. Black locust, false indigo, and smooth false indigo seedlings had high foliage nitrogen concentrations and have been shown to quickly produce effective root nodules in association with native rhizobial populations (Dawson and others 1992, Navarrete-Tindall and others 2003).

Honeylocust and Kentucky coffeetree, but not redbud, had intermediate foliage nitrogen concentrations. These three species are included in the Caesalpiniodeae subfamily, where most taxa do not exhibit nodulation. The intermediate foliar nitrogen concentration and reports of nitrogenase activity and presence of rhizobial-like bacteroids inside infections of cortical cells (Bryan and others 1996), strongly suggest honeylocust and Kentucky coffeetree can fix nitrogen, but at much lower rates than nodulated legumes. The low-foliage nitrogen concentrations for redbud were unexpected. Bryan and others (1996) measured low rates of nitrogenase activity in Judas tree (*Cercis siliquastrum* L.) when exposed to a highly diverse population of rhizobia to enhance the likelihood of finding a compatible symbiont. Perhaps efficient compatible rhizobial bacteria were not present within our old-field soils, or redbud is incapable of non-nodular nitrogen fixation.

Several reasons can be given for the lack of response by pecan to nitrogen apparently being fixed by several of the woody legumes and fertilizer treatment. Schlesinger and Williams (1984) reported that non-native nitrogen-fixing shrubs and trees increased black walnut growth on the poorest sites, but not the best sites. This observation could apply to pecan as well as soil fertility is naturally high in a deep Memfro silt loam; however, foliage nitrogen in the range of 1.8 to 2.0 indicates a nitrogen-deficiency that may not be correctable by the addition of just nitrogen. This hypothesis is partially supported by the observation that pecan foliage nitrogen was not improved in two of the four blocks that had been invaded by hairy vetch, an excellent nitrogen-fixing cover crop (White and others 1981). An alternative explanation is that fixed nitrogen is not being released into the ecosystem. It is possible the non-nodulated nurse crop trees were fixing nitrogen, but in the fall were translocating the fixed nitrogen to bark tissues rather than to the leaf litter, as found with some actinorhizal species (Dawson and others 1980). Trends in seasonal foliage nitrogen remain to be determined for the nurse crop species used in our study.

The major problem with using nitrogen-fixing trees in hardwood plantings is matching the growth of the woody nurse crop species to the crop trees. We found pecan was rapidly overtopped by black locust and will need to be coppiced multiple times if the pecan trees are to survive. False indigo and smooth false indigo were expected to stimulate early pecan height growth by adding fixed nitrogen to the soil, reducing competition from herbaceous weeds, and providing up to 3 m of side-shade. Although both species are multi-stemmed, the wide-spreading crowns allow too much light to penetrate the canopy to reduce herbaceous competition, and height growth was inadequate to provide much side shade to the pecans. Height growth of honeylocust, Kentucky coffeetree, and redbud most closely match the height growth of pecan. Although there is evidence that honeylocust is fixing nitrogen, the tendency to develop thorns on seed-origin seedlings precludes its use as a nurse crop without vegetative propagation. Saplings of Kentucky coffeetree, a common associate of pecan on bottomland sites, were slow to establish, but eventually had height growth rates similar to pecan. Additional studies with interplanted seedlings are needed to confirm the growth rates. Although redbud and pecan growth rates are compatible, the low foliage nitrogen of redbud suggests it has not formed an association with native rhizobial species. Results indicate it may be too early in the study to determine which native woody legume, if any, should be interplanted with northern pecan to improve foliage nitrogen, growth, and pecan production.

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BLACK WALNUT SUITABILITY INDEX: A NATURAL RESOURCES CONSERVATION SERVICE NATIONAL SOIL INFORMATION SYSTEM BASED INTERPRETIVE MODEL

Douglas C. Wallace and Fred J. Young[1]

Abstract.—Suitable site conditions are essential for productive growth of black walnut (*Juglans nigra* L.). Field officers at the Natural Resources Conservation Service (NRCS) in the Midwest are often asked, "What is a good walnut soil?" Current NRCS information available to most field offices rates soils only as "suitable" or "unsuitable" for black walnut. To refine the precision of this categorization and more effectively answer this question, we developed a quantified suitability model that uses 10 soil and site factors from the National Soil Information System database (NASIS). Our interpretive model generates a black walnut suitability index rating for each soil component within each soil survey map unit. Soil properties in the model are effective soil depth, available water capacity, water table depth, percent clay, percent sand, pH, and surface rock fragments. Site properties are flood frequency and duration, landform, and historic native vegetation. Linear and nonlinear functions are used to convert NASIS property values to numeric scores, which are then weighted according to relative importance in the model. Output ratings are on a continuous scale from 0.0 to 1.0, with higher values indicating better suitability. On the basis of these numeric values, the soils are grouped into the following six suitability classes: unsuited, poorly suited, somewhat suited, moderately suited, well suited, and very well suited. The final Black Walnut Suitability Index provides a rational, objective method of rating soils based on their inherent potential for black walnut growth.

INTRODUCTION

Black walnut (*Juglans nigra* L.) is a commercially valuable lumber, veneer, and nut species; provides important wildlife values; and has an extensive range across the entire Eastern United States. Black walnut displays wide ecological amplitude across many landscape positions and will grow under a variety of soil and site conditions (Williams 1990). Suitable soil and site conditions are essential for the productive, commercial growth of black walnut (Ponder 1982, Ditsch and others 1996).

A frequently asked question at the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) field office level in the Midwest is: "What is a good walnut soil?" Current NRCS Field Office Technical Guide rates soil series only as "suitable" or "unsuitable" for black walnut and is based on information from NRCS Conservation Tree and Shrub Groups. This guidance is too general for developing site-specific soil interpretations for black walnut areas that may include multiple map units and provides no scaled rating.

OBJECTIVES

To more effectively refine the precision of this categorization, we developed a quantified suitability model that uses 10 soil and site factors from the USDA National Soil Information System database (NASIS). The purpose of our paper is to describe an interpretive model that generates a black walnut suitability index rating for each soil component within each soil survey map unit.

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METHODS

Index Development

The focus of the black walnut suitability index (BWSI) was to identify critical rating criteria that would categorize a soil map unit's suitability for black walnut production. Black walnut is sensitive to a number of soil conditions and grows best on deep, well drained, nearly neutral, loamy, bottomland soils that experience periodic flooding of short duration (Losche 1973, Countryman and others 1997, Atchison 2005).

Based on black walnut growth criteria identified above and from research studies in the Midwest (Geyer and others 1980, Ditsch and others 1996, Ponder 1998, Geyer and Ponder 2004), the "ideal" black walnut soil for our model is a compilation of these factors and is defined as 1) very deep (>150 cm without a restrictive layer); 2) moderately well to well drained (water table >100 cm deep); 3) high available water capacity (AWC)(>35 cm of available water in 150 cm of soil depth); 4) slightly acid to slightly alkaline (pH 6.5 to 7.4) in the upper 60 cm; 5) medium textured (≤35 percent clay and ≤50 percent sand at 25-60 cm depth); 6) no rock fragments in the upper 60 cm; 7) a forest-derived soil; and 8) a floodplain site with no to brief duration (2 to <7 days) flooding.

In addition, inappropriate black walnut soil and site factors (Geyer and others 1980, Ponder 1982, and Parker and others 1992) are used to create unsuitable ratings for the model. These factors include: 1) shallow soil depth (<50 cm to a retarding layer); 2) wetness (water table <15 cm); 3) low available water capacity (<7.6 cm in 150 cm of soil depth); 4) very long-duration flooding (>30 days); and 5) >50 percent subsoil clay or >90 percent subsoil sand. All other combinations of soil and site factors between an ideal soil map unit component and an unsuited soil map unit component are rated as intermediate in suitability.

Based on these key growth criteria for black walnut, our quantified suitability model uses 10 soil and site factors from the NASIS database to generate soil ratings for black walnut. Soil properties in the model are as follows: 1) effective soil depth; 2) available water capacity; 3) water table depth; 4) texture (percent clay and percent sand); 5) pH (low and high); and 6) surface layer rock fragments. Site properties are: 1) flood frequency; 2) flood duration; 3) landform; and 4) historic native vegetation. Table 1 displays a summary of these factors, their generated membership values used in the index, and explanations of criteria.

Interpretation Structure

Structured Query Language is used to access and manipulate the NASIS database. Linear and nonlinear functions and assigned values are used to convert NASIS property values to numeric scores, which are then weighted according to relative importance in the model. Output ratings are on a continuous scale from 0.0 to 1.0, with higher values indicating enhanced suitability.

The BWSI model structure (Fig. 1) combines individual rules into two major groupings, an additive rule and a multiplicative rule. The multiplicative rule contains four subrules for soil properties that can restrict black walnut suitability, and is used as a multiplier in the model to strongly impact the final index. The soil properties rated in the multiplier subrules are: 1) depth to bedrock; 2) flood duration; 3) AWC; and 4) soil wetness. The multiplicative rule returns the lowest rating of its four subrules, and multiplies this rating with the output from the additive rule. This step has the effect of overriding other soil property values of lesser importance. For example, if depth to bedrock is less than 50 cm for a given soil map unit (one of the unsuited criteria), the other soil properties are now irrelevant. Such a map unit would be rated 0 on the depth to bedrock subrule, and the resulting multiplicative rule value of 0 would, when multiplied with the additive rule value, insure that the soil is rated as unsuited.

Table 1.–Black walnut suitability index multiplicative and additive factors with explanations and associated criteria values

Factors	Explanation	Criteria Value
		Multiplicative Factors
Depth limit	Soil depth to bedrock or restrictive pan	• <50 cm = 0 • ≥50 cm = 1
Flood duration	Flooding duration in May	• None to brief (0 to <7 days) = 1 • Long (7 to 30 days) = 0.5 • Very long (>30 days) = 0
AWC limit	Available water capacity from 0 to 150 cm	• <7.6 cm = 0 • ≥7.6 cm = 1
Wetness	Water table depth in April	Piecewise linear function from 0 to 1 based on 4 datasets: • ≤15 cm = 0 • 30 cm = 0.5 • 60 cm = 0.75 • ≥100 cm = 1)
		Additive Factors
Depth	Soil depth to restricting (e.g., bedrock, fragipan) and/or retarding (e.g., abrupt textural change, densic material) layer of any kind from 50 to 150 cm	Sigmoid curve scaled from 0 to 1. • 50 cm = 0 • 150 cm = 1
Texture	Percent of subsurface (25-60 cm) clay or sand	Piecewise linear function from 1 to 0 based on datasets: • Clay: ≤35 percent = 1; 40 percent = 0.5; >50 percent = 0 • Sand: ≤50 percent = 1; 60 percent = 0.9; 70 percent = 0.7; 80 percent = 0.2; >90 percent = 0
AWC	Total available water capacity from 0 to 150 cm (entire profile)	Sigmoid curve scaled from 0 to 1. • 0 cm = 0 • >35 cm = 1
pH	Soil pH (water) from 0 to 60 cm	Sigmoid curve scaled from 0 to 1. • Low pH: 4.0 = 0; ≥6.5 = 1 • High pH: 8.5 = 0; <7.4 = 1
Fragments	Percent of rock fragments greater than 5 cm in diameter in top 60 cm of soil profile	Sigmoid curve scaled from 1 to 0. • 0 percent = 1 • >35 percent = 0
Flood frequency	Flooding frequency in May	• None or rare (0 to 5 percent chance in any year) = 0 • Occasional (5 to 50 percent chance in any year) or frequent (more than 50 percent chance in any year) = 1
Landform	Landform designation	• Ridge/shoulder = 0 • Backslope = 0.33 • Footslope/terrace = 0.67 • Floodplain = 1
Historic vegetation	Historic vegetation with landscape position	• Upland prairie = 0 • Floodplain/terrace prairie = 0.33 • All mixed forest and prairie = 0.67 • All forest/woodland = 1

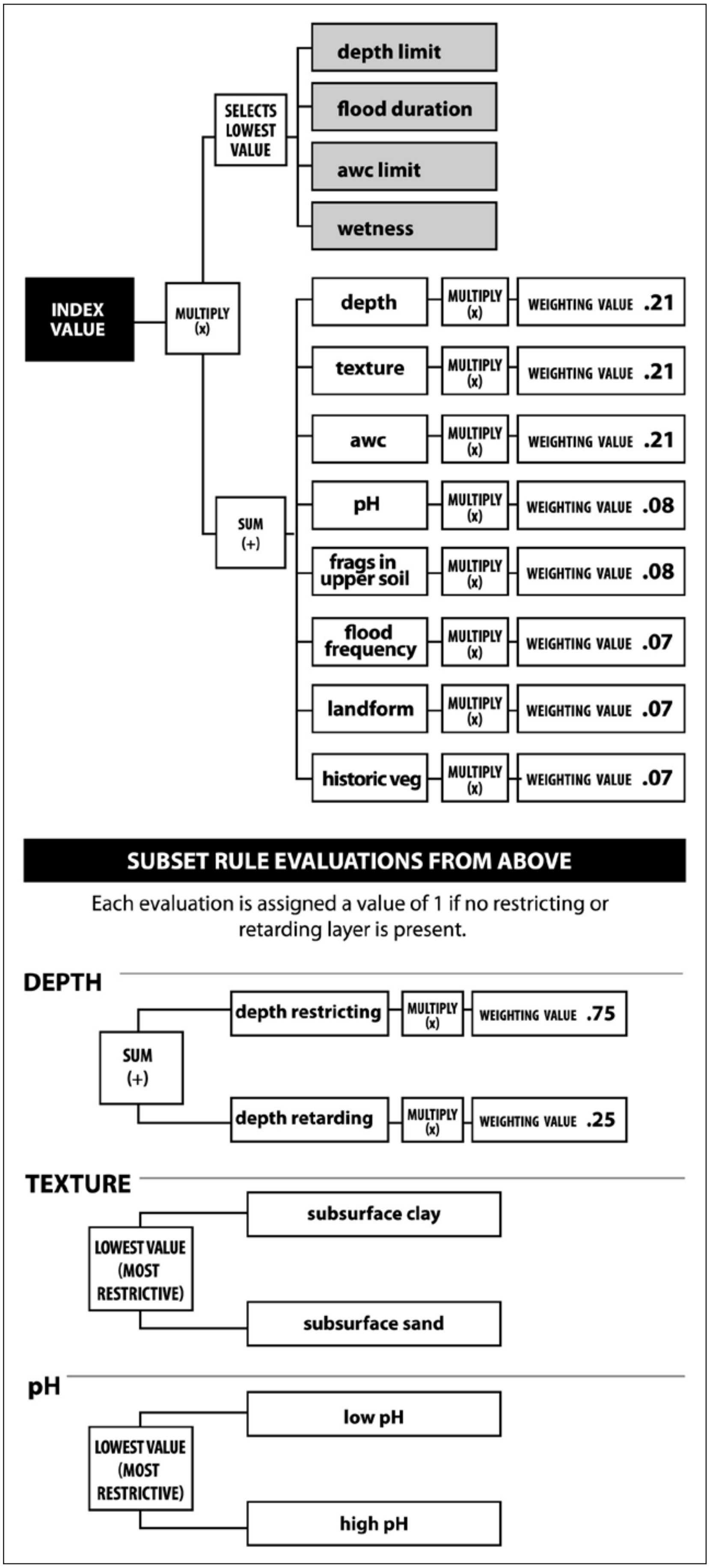

Figure 1.—The BWSI model structure showing individual rules. If one of the multiplicative factors (gray shading) is 0, the soil is rated 0 (unsuited). If all the multiplicative factors are 1, the sum of the additive factors will be the basis for rating the soil. If the lowest of the multiplicative factors is between 0 and 1, the sum of the additive factors will be multiplied by this value, thereby reducing the final suitability index. The final index is derived by multiplying the additive and multiplicative rules together.

Table 2.—Black walnut suitability qualitative rating index with corresponding calculated Index values based on eight additive and four multiplicative factors associated with black walnut growth

Black Walnut Suitability Index Rating	
Qualitative rating	Calculated value
Very well suited	0.976 - 1.000
Well suited	0.800 - 0.975
Moderately suited	0.600 - 0.799
Somewhat suited	0.400 - 0.599
Poorly suited	0.200 - 0.399
Unsuited	0.000 - 0.199

The additive rule creates gradations between fully and partially suited soil map units. The additive rule contains eight subrules: 1) soil depth; 2) texture; 3) AWC; 4) pH; 5) fragments in the upper soil; 6) flooding frequency; 7) landform; and 8) historic vegetation. Four of these additive subrules are compound: 1) pH (low and high); 2) soil depth (restricting and retarding layers); 3) historic vegetation (historic vegetation with landscape interaction); and 4) texture (sandy and clayey). Each subrule is weighted to reflect its relative importance. Weighted values for the additive subrules were assigned based on regression analysis results by Geyer and others (1980) and Geyer and Ponder (2004) and on the qualitative statements of other researchers (Losch 1973, Parker and others 1992, Ditsch and others 1996). Soil depth, texture, and available water capacity were consistently cited as major influencing factors relative to black walnut growth. Accordingly, these three subrules are weighted higher in the model. The weighted values of the eight subrules are then added to create the final additive rule value. If the multiplicative rule value is one (no restrictions) then the additive value will determine the final Index value. If the multiplicative rule value is greater than 0 but less than 1, (e.g., wetness or flooding is >0 or <1), the final index value will be a multiplicative factor of the additive rule summed values.

On the basis of these numeric values, the soils are grouped into six suitability classes (Table 2). These classes are identified as unsuited, poorly suited, somewhat suited, moderately suited, well suited, and very well suited. The qualitative rating breaks are arbitrary. The two highest rating categories, very well suited and well suited, are established with smaller numerical ranges to create a more limited rating class than the others. The remaining four qualitative rating classes are then evenly divided with numerical breaks.

RESULTS AND DISCUSSION

The BWSI is currently attached exclusively to Missouri data sets in the NRCS Soil Data Mart (SDM). Annually, Missouri NRCS refreshes its soils database by recalculating all soil interpretations in NASIS, including the BWSI, and exporting these refreshed data to the SDM. Any revisions to the soils database that have occurred over the year are captured in this process.

Other states may interface the BWSI on their state's soils. The state soils database administrator can then include the Index on the SDM and in the NRCS Web Soil Survey (WSS) but will be responsible for maintenance of their specific BWSI.

Table 3.–Black Walnut Suitability Index output table example from the Web Soil Survey for selected map units from Boone County, MO. This output table identifies up to the top five limiting rating reasons and their associated values. Values shown in parentheses under the "Rating reasons" column represent the rating values generated by each subrule in the model.

Map unit symbol	Map unit name	Rating	Rating reasons (rating values)
64008	Freeburg silt loam, 2 to 5 percent slopes	Somewhat suited	Flood Freq: None/Rare (0.00)
			pH limiting factor (0.26)
			Watertable: 30-60 cm (0.61)
			Landform: Footslope/ Terrace (0.75)
			Available water capacity: 20-30 cm (0.94)
66000	Moniteau silt loam, 0 to 2 percent slopes, occasionally flooded	Unsuited	Watertable: < 15 cm (0.00)
			pH limiting factor (0.08) Landform:
			Footslope/ Terrace (0.75)
			Available water capacity: 20-30 cm (0.93)
66014	Haymond silt loam, 0 to 3 percent slopes, frequently flooded	Very well suited	Available water capacity: 20-30 cm (0.94)

Running the BWSI can be accomplished through NASIS, the WSS, and the SDM. In WSS, the BWSI is under the Vegetative Productivity pull-down menu of the Suitability and Limitation for Use tab, under Soil Data Explorer. It is also located under the Soil Reports tab. In SDM, BWSI is one of the choices within the Selected Soil Interpretations report. NASIS web access is restricted to authorized USDA individuals and is controlled by individual state soil survey staffs. Access to WSS and SDM is open to anyone using the internet. Their respective URL's are http://websoilsurvey.nrcs.usda.gov/app/ and http://soildatamart.nrcs.usda.gov/ . Each of the open web sites has different multi-step procedures with multiple output display options. The WSS can generate site-specific black walnut suitability interpretive maps as well as associated tabular outputs by soil map unit. SDM outputs are limited to tabular outputs by soil map unit. Table 3 displays an example of the tabular output from the WSS.

No quantitative field testing of the BWSI has been conducted. However, field observations, along with examination of BWSI output for soil map units of known black walnut suitability, indicate that the Index displays an acceptable degree of accuracy. User comments have been positive. Whichever web site is used, the BWSI provides a new rational, objective method of rating soil map units based on their inherent potential soil properties for black walnut growth.

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