Diameter-Limit Harvesting: Effects of Residual Trees on Regeneration Dynamics in Appalachian Hardwoods

Travis Deluca, Mary Ann Fajvan, and Gary Miller

ABSTRACT

Ten-years after diameter-limit harvesting in an Appalachian hardwood stand, the height, dbh, and basal area of sapling regeneration was inversely related to the degree of "overtopping" of residual trees. Black cherry and red maple were the most abundant saplings with 416.5 ± 25.7 and 152.9 ± 16.8 stems per acre, respectively. Models of black cherry height and diameter showed significant negative relationships ($P < 0.05$) with residual tree basal area. In addition, height, diameter, and basal area of dominant and codominant black cherry and black birch saplings were inversely related to residual tree basal area ($P < 0.05$), as was the basal area of red maple saplings. Alternatively, red maple sapling diameter had a significant positive relationship ($P < 0.05$) with residual basal area, and height was not significantly affected. Findings suggest that overall stand conditions were most favorable for the development of shade-tolerant red maple, with shade-intolerant species developing well in open areas. However, the long-term development of black cherry may be jeopardized by side shade and canopy cover. Removal of residual trees and subsequent cleaning operations are recommended to increase growth rates of shade-intolerant sapling regeneration.

Keywords: diameter-limit harvesting, black cherry, red maple, hardwood sapling development

Numerous silvicultural guidelines exist for sustaining the productive capacity and tree species diversity of North America's eastern deciduous forests (e.g., Roach and Gingrich 1968, Smith and Eye 1986, Nyland 1987, Marquis et al. 1992). For mature stands, these recommended management practices focus on establishing new cohorts containing species representative of the forest that preceded them. However, silvicultural treatments aimed at guiding stand development and promoting sustainability are not being implemented on the majority of private forest ownerships (Fajvan et al. 1998, Pell 1998, Fajvan 2006, Stringer 2008). Most forest ownerships in this region are privately owned (Birch 1996), and there is a tendency to exploit high-value tree species for short-term financial gain without consideration for their renewal (Nyland 1992). Such nonsustainable harvesting practices affect biodiversity, ecosystem integrity, wildlife habitat, and long-term financial returns (Ezell 1992, Weakland et al. 2002, Schuler 2004, Munsell et al. 2008).

The common practice of diameter-limit harvesting removes trees larger than a specified diameter. It can provide high short-term financial returns because, typically, only merchantable sawtimber is removed (Filip 1967, Reed et al. 1986, Erickson et al. 1990). Particularly in even-aged stands, residual stand quality is affected because the largest, most vigorous trees with good stem form are removed, leaving slower-growing, poorer-quality stems in the stand (Blum and Filip 1963, Hart 1964, Miller and Smith 1991, Nyland 1992). This practice leaves a spatially irregular distribution of residual trees (Oliver and Larson 1996) with some portions of the stand well stocked and others with little to no overstory (Blum and Filip 1963, Hart 1964, Trimble 1971, Grushecky and Fajvan 1999). Diameter-limit harvesting combined with other disturbances, such as insect defoliation (Archambault et al. 2006) and/or deer browsing (Latham et al. 2005, Fajvan 2006), further complicates postharvest vegetation development. In even-aged stands, a high degree of structural complexity can develop over time from diameter-limit harvesting. Regeneration initiates in the more open areas, and individual tree growth is affected by spatially variable degrees of crowding and exposure. Traditional management tools for predicting growth and yield do not consider such spatial irregularity and are likely unreliable as well for forecasting the dynamics of these stand structures (Canham et al. 2004).

In eastern hardwood forests, diameter-limit harvesting can lead to the loss of seed sources of shade-intolerant species, because these are often the largest stems in a stand (Fajvan et al. 1998). Also, residual trees can create unfavorable conditions for the regeneration of shade-intolerant species (Miller and Kochenderfer 1998) and their subsequent development (Miller et al. 2006). Consequently, tree species biodiversity can also be reduced (Schuler 2004). Especially if harvests are repeated, over time, postharvest stands are dominated by shade-tolerant regeneration (Smith and Miller 1987, Trimble 1973a, Heiligmann and Ward 1993).

Uncut Appalachian hardwood stands typically contain 20–30 tree species (Miller and Kochenderfer 1998) that coexist in multilayered canopies stratified by species and growth rate (sensu Oliver and Larson 1996, Tift and Fajvan 1999). By opening the canopy,

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diameter-limit cutting promotes growth of shade-tolerant subcanopy species, which creates low shade on the forest floor (Barden 1981, Runkle and Yetter 1987, Poulson and Platt 1989, McClure and Lee 1992). Expansion of the lower canopy strata can hinder the growth and development of shade-intolerant regeneration (Fajvan and Wood 1996). In addition, the unplanned location and arrangement of residual trees creates a variety of microsites, causing an irregular distribution of regeneration.

Except for clearcutting, even-aged silvicultural reproduction methods rely on planned residual structures and stem densities. Trees to be removed are marked systematically to create environmental conditions favorable to particular species. For example, retention of widely spaced, large seed trees following uniform, shelterwood establishment cuts provides favorable environments for the regeneration of shade-intolerant and tolerant species (Grushecky and Fajvan 1999, Ray et al. 1999). However, if overstories are not removed in a timely manner, growth stagnation of the new cohort may result (Assman 1970). Planned residual structures and appropriate timing of subsequent harvests to regulate stand density allows managers some control over regeneration composition and growth rate.

Residual trees resulting from diameter-limit harvests tend to have smaller crowns than those favored in silvicultural treatments (Grushecky and Fajvan 1999), and these stems are usually aggregated throughout the stand (Trimble 1971), especially when diameter limits are set fairly low (Grushecky and Fajvan 1999). Irregular residual stocking affects the spatial distribution of regenerating species because open areas will have more sunlight than areas beneath clusters of residual trees. Thus, shade-intolerant species will be favored over shade-tolerant species in larger openings created by the harvest (Canham 1989). Site resources in the vicinity of residual trees will be more limited, especially for seedlings growing directly under the crowns (Zinke 1962, Assman 1970, Miller at al. 2007).

This study examined the effects of diameter-limit cutting on regeneration dynamics in an Appalachian hardwood stand. We measured the species, size (height and diameter), and spatial distribution of regeneration located near residual trees 10 years after harvest. Specifically, we tested if (1) the presence of residual trees would favor the development of shade-tolerant species compared with shade-intolerant ones and (2) the density of residual overstory trees had a negative effect on regeneration size.

Methods

Study Area and Stand History

The study area is located in a 75-year-old mixed mesophytic hardwood stand (Braun 1950) within the 8,000-ac West Virginia University Research Forest in Monongalia County, West Virginia. The even-aged stand originated after clearcutting and has never been thinned. The overstory was dominated by northern red oak (*Quercus rubra* L.) and yellow-poplar (*Liriodendron tulipifera* L.) with lesser amounts of chestnut oak (*Quercus prinus* L.), white oak (*Quercus alba* L.), red maple (*Acer rubrum* L.), and black cherry (*Prunus serotina* Ehrh.). The stand basal area was 150 ft^2/ac with yellow-poplar and red oak composing 50 and 30%, respectively. Because of browsing pressure from white-tailed deer, advance regeneration of most species was scarce. The most abundant seedlings in 1992 (≥20 in. tall) were black cherry and red maple, averaging 75 and 50 stems/ac, respectively (Fajvan 2006). Soils on the site consist of Dekalb channery loam on slopes ranging from 8 to 15%, and Dekalb very stony loam on slopes ranging from 3 to 65% (USDA Soil Conservation Service 1982).

During autumn 1993, all merchantable trees >16 in. in diameter at 4.5 ft. above the ground (dbh) were harvested from four, 10-ac treatment blocks. These areas represented one of the treatments established as part of a larger study examining the long-term vegetation effects of harvesting to different diameter limits (Fajvan 2006). Immediately after the harvests, residual basal areas (stems ≥5-in. dbh) within the four blocks ranged from 30 to 60 ft^2/ac. Of the basal area removed, 89% consisted of red oak and yellow-poplar because these species were the largest (dbh). The harvest coincided with a bumper acorn crop that resulted in abundant oak regeneration; advance regeneration of oak was scarce before harvest (Fajvan 2006). By 2003, basal areas ranged from 75 to 102 ft^2/ac.

Overstory Tree and Transect Measurements

In 2003, we conducted a 100% inventory of stems with ≥5-in. dbh in each treatment block. From these data, 217 "subject" trees were systematically sampled (Shiver and Borders 1996) from among the species and diameters present in the residual stands. Slope percent and aspect at the subject tree's location were recorded. Other measurements included species, total height, dbh, height to base of live crown, and the crown radius along the 0, 90, 180, and 270° azimuths. The spatial distribution of residual stems and open areas was very irregular with few distinct boundaries between isolated stems, tree clumps, and canopy openings (Grushecky and Fajvan 1999). Because the area was not homogeneous, sampling of saplings was stratified in proportion to subject tree crown size and the area adjacent to these crowns (Shiver and Borders 1996), whether open or occupied by another tree crown.

Four transects for regeneration sampling were located along the crown radius azimuths of each subject tree (Miller et al. 2006). Each transect was 5 ft wide (Figure 1) and the length was equal to the crown radius plus an additional 5 ft; therefore, transect length was variable. Subject residual trees consisted of 75 yellow-poplar, 55 each of red/black oaks and red maple, and 16 each of white oak and chestnut oak. Diameters ranged from 11 to 16 in. dbh, except for red maple which ranged from 7 to 11 in. dbh.

Regeneration of all stems with ≥0.6 in. dbh was tallied along the transects. Total sapling height was measured using a telescoping height pole in addition to recording species, dbh, crown class (evaluated within the understory stratum), and distance from the bole of the subject tree. Because of intensive deer browsing, most oak saplings were less than 0.6 in. in diameter. Therefore, all oaks ≥4.5 ft. tall were included in the tally because oak had been a major component in the original stand.

Sapling location was categorized relative to the crowns of the 217 subject trees. Stems growing only beneath the crown of the subject tree were categorized as "under," Saplings growing outside the subject tree crown were considered "out" and those outside the canopy of the subject tree, but under the canopy of one or more residual trees were "out2." Stems growing under both the subject tree and another residual overstory tree with an overlapping crown, were categorized as "under2" (Figure 1).

Overstory basal area in the vicinity of each subject tree was measured by recording the diameters of all residual trees in a ⅒ ac circular plot centered around the subject tree. These measurements were also collected in 2003, 6 months after the transect data. By that time, 30 of the subject trees had been harvested. Therefore, plot basal areas were measured for only 187 of the original 217 subject

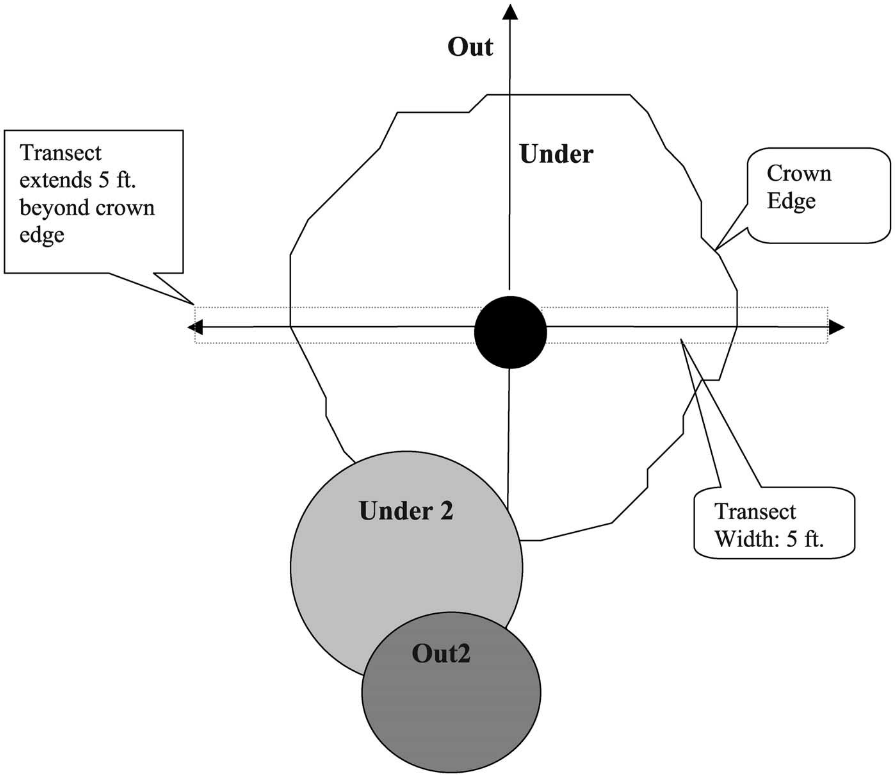

Figure 1. Sapling sampling transects established along four crown radii of subject trees. Sapling locations were categorized as either "under" (beneath the crown of only the subject tree), "out" (outside the canopy of the subject tree), "out2" (outside the subject tree crown but under the crown[s] of other residual trees), and "under2" (under both the subject tree and another residual tree).

trees, thereby limiting the evaluation of residual stand density on sapling development to a subset of the original transect data.

Analysis

Crown areas for the 217 subject trees were determined by averaging the four radii and calculating circular area. Inequality of basal area per acre among residual tree species was tested and species differences in crown projection area of subject trees were compared with an analysis of variance using the general linear models procedure (SAS Institute, Inc., 2004). Duncan's new multiple range test was used to compare basal area per acre and crown projection area means between individual overstory species.

Understory Summary

The rectangular area of each transect was determined and the number of saplings per acre and their associated basal area were extrapolated and averaged for each subject tree. Sapling species abundance was calculated as: the number of saplings per acre of a species divided by the total number of saplings per acre. Data were then combined across all stands for analyses.

Means of total height and dbh were calculated for saplings according to species and shade tolerance group, which allowed inclusion of species with low abundance. The shade-intolerant group was composed of black cherry, black birch (*Betula lenta*), yellow-poplar, pin cherry (*Prunus pennsylvanica*), black locust (*Robinia pseudoacacia*), sassafras (*Sassafras albidum*), and sumac (*Rhus* spp.). The shade-tolerant group was red maple, black gum (*Nyssa sylvatica*), hickory (*Carya* spp.), striped maple (*Acer pennsylvanicum*), sour wood (*Oxydendrum arboretum*), and dogwood (*Cornus spp.*). The oaks were not included in these groups because of the different sampling (tree size) criteria. All shade tolerance ratings were according to Burns and Honkala (1990).

Species differences in sapling heights, diameters, and basal areas were compared for the 217 subject trees using general linear mixed model analysis (SAS Institute, Inc., 2004) with log transformation of all variables to achieve normality. Sapling basal area was used as a comparison variable because it incorporates stem density and size (diameter). Species with ≥100 individual stems were analyzed individually: black cherry, black birch, red/black oak, red maple, sassafras (*S. albidum*), and yellow-poplar. The analyses were also conducted with intermediate and overtopped stems removed from the data set and between shade tolerance groups. Estimate statements were used to compare sapling size and basal area among species and shade tolerance groups.

A general linear mixed model with repeated measures was used to compare mean sapling height, dbh, and basal area relative to location (out, under, out2, and under2). Fixed terms were the main effects of species, location (repeated factor), and their interaction, and overstory basal area was included as a covariate. "Location" is considered the repeated factor because each subject tree is sampled at four locations (transects) and the data are spatially autocorrelated. The model was also tested substituting shade tolerance group for species as fixed terms. Dummy variables for the categorical effects of sapling location were included in the regression analysis to test the assumption of common slopes.

An analysis of covariance for transects associated with the subset of 187 subject trees was used to test whether the slope of the overstory basal area term in each model equaled zero. Because overstory basal area had significant effects on sapling total height and dbh, unequal slope models were developed to examine the relationship of

Table 1. Mean total height, dbh, and basal area per acre (± standard error), of the six most abundant saplings; dominant and codominant stems only; and species grouped according to shade tolerance. Trees per acre (± standard error) and percent species abundance are also included for each species.

Species/shade tolerance[a]	Height (ft)	dbh (in.)	Basal area (ft^2/ac)	Trees/ac	Species abundance (%)
Black cherry (*n* = 904)	15.9 (0.3)	1.1 (0.0)	1.6 (0.1)	416.5 (25.7)	38
Dom/codom stems (*n* = 120)	23.8 (0.8)	1.9 (0.0)	1.1 (0.2)		
Black birch (*n* = 228)	16.1 (0.5)	1.1 (0.1)	0.6 (0.1)	121.0 (13.0)	11
Dom/codom stems (*n* = 34)	22.6 (1.2)	1.9 (0.2)	0.3 (0.1)		
Red maple (*n* = 318)	17.4 (0.5)	1.5 (0.1)	1.4 (0.2)	152.9 (16.8)	14
Dom/codom stems (*n* = 45)	23.6 (1.0)	2.3 (0.1)	0.7 (0.2)		
Yellow-poplar (*n* = 177)	17.0 (0.8)	2.1 (0.2)	0.9 (0.2)	92.8 (12.6)	8
Dom/codom stems (*n* = 25)	24.1 (1.3)	1.3 (0.1)	0.4 (0.1)		
Red/black oak[b] (*n* = 248)	7.9 (0.5)	0.6 (0.1)	0.3 (0.1)	126.3 (13.8)	12
Sassafras[2] (*n* = 159)	15.6 (0.6)	1.1 (0.1)	0.4 (0.1)	73.9 (8.9)	7
Shade intolerant (*n* = 1,492)	17.0 (0.7)	1.4 (0.1)	2.7 (0.2)	731.2 (30.2)	
Shade tolerant (*n* = 400)	20.2 (1.1)	2.1 (0.2)	2.3 (0.2)	225.4 (11.4)	

[a] Shade intolerant: Black cherry, black birch, yellow-poplar, pin cherry, black locust, and sassafras. Shade tolerant: Red maple, black gum, striped maple, sourwood, and dogwood.

[b] Insufficient dominant/codominant stems for analysis.

Codom, codominant; Dom, dominant.

overstory basal area and regeneration size for each species and shade tolerance group. The assumption of a heterogeneous autoregressive covariance structure was the most feasible.

Results

Stand Structure in 2003

Yellow-poplar had the highest residual overstory basal area (23.5 ± 1.9 ft^2/ac) and red maple basal area (16.4 ± 0.9 ft^2/ac) was greater than the basal area of chestnut oak (9.0 ± 1.2 ft^2/ac), white oak (3.5 ± 0.5 ft^2/ac), and black cherry (2.3 ± 0.4 ft^2/ac). Red/black oak basal area (15.6 ± 1.0 ft^2/ac) was greater than chestnut oak, white oak, and black cherry. Yellow-poplar had the smallest crown projection area (287.7 ± 19.0 ft^2) and red/black oak had a greater crown projection area (472.5 ± 35.1 ft^2) than red maple (365.1 ± 24.2 ft^2) and white oak (304.8 ± 40.2 ft^2).

There were 1,080 saplings/ac for all species. The most abundant species was black cherry, followed by red maple, red/black oak, black birch, yellow-poplar, and sassafras (Table 1). Striped maple, sour wood, black gum, dogwood, white ash, black locust, hickory, and chestnut oak all had a minor presence (<1%).

Among black cherry, black birch, red maple, and yellow-poplar, heights of dominant and codominant stems averaged around 23 ft, about 6–7 ft taller than all crown classes combined (Table 1). When averaged over all crown classes, black birch and red maple saplings were taller than sassafras, and sassafras was shorter and had smaller dbh than yellow-poplar. Black cherry saplings were shorter than red maple and yellow-poplar, and both black cherry and black birch saplings had smaller average dbh than these species. Saplings of the red/black oak group were shorter and had smaller dbh than the other five species. All of these comparisons were significant ($P = 0.005$ to <0.0001; Table 1).

Black cherry saplings had the highest total basal area, but basal area of dominant and codominant saplings was only significantly greater than that for yellow-poplar and black birch. Red maple sapling basal area was greater than sassafras and yellow-poplar. Dominant/codominant maple saplings had larger dbh than black cherry and black birch, and they also had greater basal area than black birch. Yellow-poplar sapling basal area was greater than sassafras. Basal area of red/black oak saplings was less than black birch, red maple, black cherry, and yellow-poplar. As a group, shade-

Table 2. Contrasts of species height, dbh, and basal area means (± standard error); comparisons are by locations relative to subject tree and adjacent tree(s) crowns, for the six most abundant species and shade-tolerance groups.

Species location	Black birch (*n* = 228)	Black cherry (*n* = 904)	Red/black oak (*n* = 248)	Red maple (*n* = 318)	Sassafras (*n* = 159)	Yellow-poplar (*n* = 177)	Shade intolerant (*n* = 1,492)	Shade tolerant (*n* = 400)
Height (ft)								
Out	18.9 (0.9)	17.2 (0.5)	8.5 (0.9)	17.3 (1.0)	16.3 (0.9)	18.5 (0.9)	19.9 (1.4)	26.7 (1.9)
n	79	332	57	60	40	52	510	94
Under	16.9 (0.6)	16.0 (0.43)	8.0 (0.6)	17.1 (0.5)	14.4 (0.7)	18.2 (0.7)	18.6 (0.9)	26.6 (1.1)
n	117	474	141	202	92	110	808	243
Out2	15.5 (1.5)	16.0 (0.8)	8.1 (1.4)	19.1 (1.4)	15.5 (1.5)	15.3 (2.0)	15.9 (1.8)	16.8 (3.2)
n	13	62	17	26	12	5	92	29
Under2	13.4 (1.0)	14.5 (0.7)	7.1 (0.9)	16.1 (1.0)	16.0 (1.5)	15.9 (1.8)	13.8 (1.2)	12.8 (1.7)
n	19	36	33	30	15	10	82	34
dbh (in.)								
Out	1.2 (0.1)	1.2 (0.1)	0.7 (0.1)	1.3 (0.1)	1.1 (0.1)	1.5 (0.1)	1.7 (0.2)	3.3 (0.3)
Under	1.1 (0.1)	1.1 (0.1)	0.6 (0.1)	1.4 (0.1)	1.0 (0.1)	1.4 (0.1)	1.6 (0.1)	2.5 (0.2)
Out2	0.9 (0.2)	1.2 (0.1)	0.7 (0.2)	1.8 (0.2)	1.0 (0.2)	1.2 (0.2)	1.1 (0.3)	1.6 (0.2)
Under2	0.9 (0.1)	1.0 (0.1)	0.6 (0.1)	1.5 (0.01)	1.1 (0.2)	1.2 (0.2)	1.1 (0.2)	1.1 (0.3)
Basal area (ft^2)								
Out	0.03 (0.006)	0.03 (0.004)	0.006 (0.004)	0.03 (0.007)	0.01 (0.002)	0.03 (0.007)	0.08 (0.01)	0.15 (0.02)
Under	0.02 (0.003)	0.03 (0.003)	0.005 (0.001)	0.04 (0.004)	0.01 (0.003)	0.04 (0.005)	0.08 (0.01)	0.12 (0.01)
Out2	0.0007 (0.003)	0.01 (0.002)	0.005 (0.003)	0.03 (0.01)	0.008 (0.002)	0.009 (0.003)	0.009 (0.001)	0.03 (0.007)
Under2	0.003 (0.001)	0.008 (0.001)	0.004 (0.002)	0.008 (0.007)	0.01 (0.004)	0.01 (0.01)	0.02 (0.001)	0.02 (0.005)

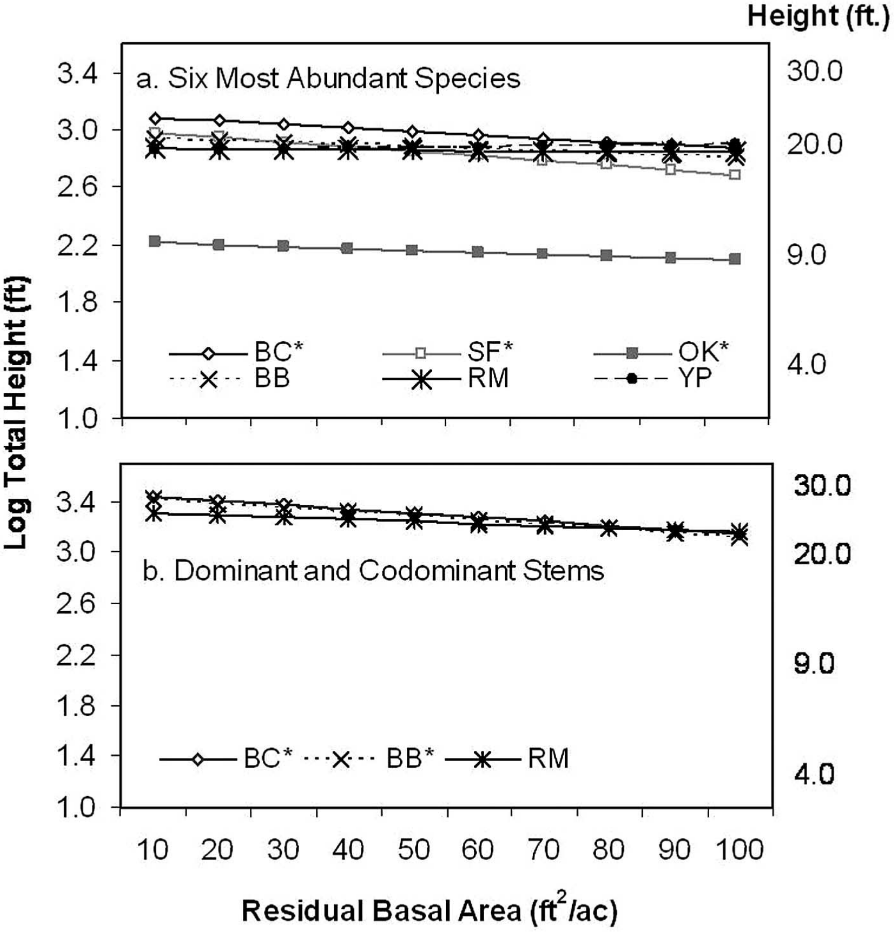

Figure 2. Sapling height profiles resulting from modeling height as a polynomial function of residual stand basal area. An asterisk (*) delineates a significant ($P < 0.05$) linear relationship. Height data were log transformed before analysis. Graphs depict the relative effects of residual trees on height structure of different species and crown class. BC, black cherry; BB, black birch; OK, red/black oak; RM, red maple; SF, sassafras; and YP, yellow-poplar.

tolerant saplings were taller and had larger dbh than those of shade-intolerant saplings. All of these comparisons were significant ($P =$ 0.04 to $<$0.0001; Table 1).

The Effects of Residual Trees on Regeneration

Within-species comparisons indicated that sapling basal area of black birch, black cherry, red maple, and yellow-poplar were always lower when trees were located in the "under2" position. Otherwise, there was no difference in sapling density relative to residual trees (Table 2). Contrasts of species basal area means for both the "under" and the "under2" locations indicated that the mean basal areas for yellow-poplar and red maple were greater than any other species (Table 2). Basal area of sassafras was less than that for red maple and yellow-poplar in all locations, and less than black cherry, except for the "under2" location. Basal area of black birch was less than black cherry, red maple, and yellow-poplar except for the "out" location. All of these comparisons were significant ($P = 0.02$ to $<$0.0001; Table 2).

Mean height and diameter of shade-tolerant species was greater ($P < 0.0001$) than shade-intolerant species in all locations. Basal areas of shade-tolerant species located in "out" and "under" locations were greater ($P < 0.0001$) than basal areas of shade-intolerant species in those locations (Table 2).

Results from the analyses of the 187 subject trees indicated that heights of black cherry, red/black oak, and sassafras saplings had a negative relationship with residual basal area (Figure 2a), and heights of dominant and codominant black cherry and black birch saplings had a similar relationship (Figure 2b). Black cherry sapling diameter had a negative relationship with residual basal area (Figure 3a), as did dominant and codominant black birch, black cherry, and red maple saplings (Figure 3b). Similarly, sapling basal area decreased with increasing overstory basal area for black birch, black cherry, and red maple (Figure 4a). However, red maple sapling diameter averaged for all crown classes had a positive relationship with residual basal area (Figure 3a).

Discussion

Effects of Residual Trees on Regeneration Structure

Regardless of their shade tolerance, saplings were taller and larger in diameter when located outside the crown influence of residual trees. Saplings of red maple and black cherry dominated the shade-tolerant and shade-intolerant species groups, respectively. Before harvest, black cherry represented only 10% of overstory basal area; yet, it was the most abundant advance regeneration species and the most abundant sapling 10 years later (Fajvan 2006). Factors contributing to black cherry's dominance likely include frequent seed

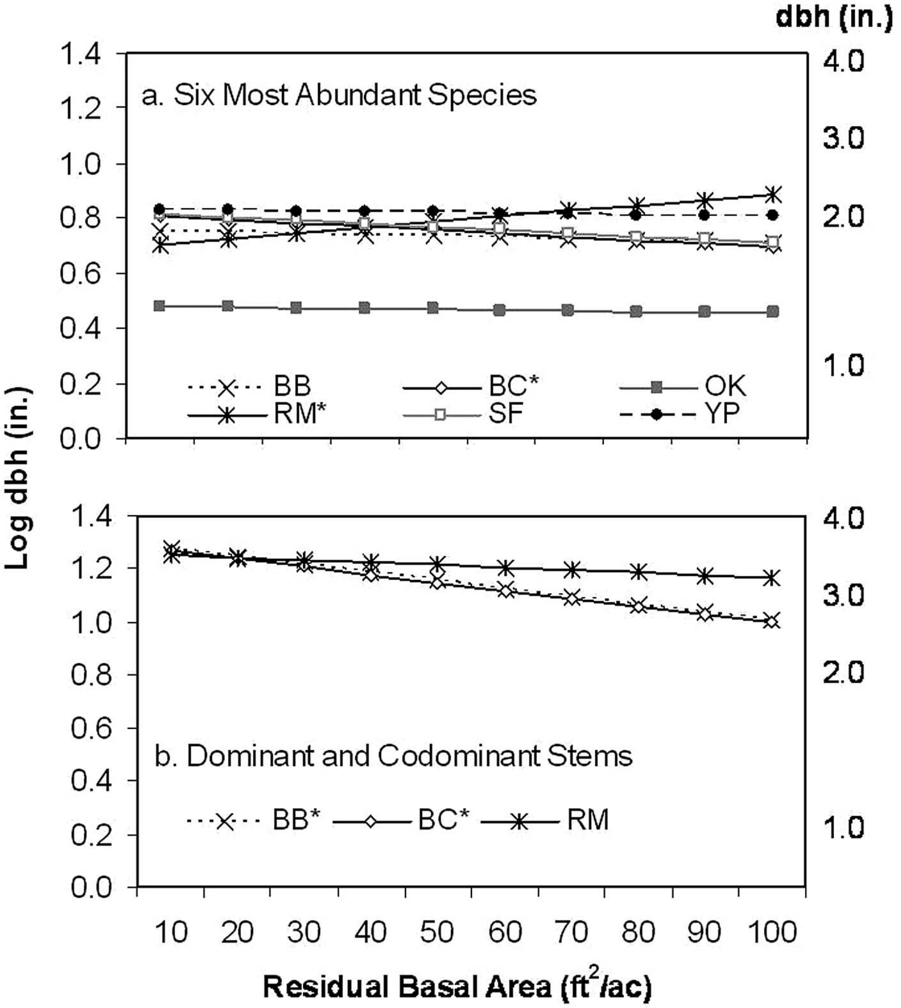

Figure 3. Sapling dbh profiles resulting from modeling dbh as a polynomial function of residual stand basal area. An asterisk (*) delineates a significant ($P < 0.05$) linear relationship. Diameter data were log transformed before analysis. Graphs depict the relative effects of residual trees on dbh structure of different species and crown class. BC, black cherry; BB, black birch; OK, red/black oak; RM, red maple; SF, sassafras; and YP, yellow-poplar.

crops (Grisez 1975) with 3-year viability in the forest floor (Wendel 1977), high relative shade tolerance as seedlings (Burns and Honkala 1990), low preference as deer browse (Latham et al. 2005), and significant height growth increases after disturbances create new growing space (Marquis 1979, 1982). The 1993 diameter-limit cut released the black cherry advance regeneration, which is still thriving in canopy gaps, but losing vigor in shaded areas.

Diameter-limit cutting, like all partial disturbances, accelerates red maple recruitment into the overstory (Abrams and Nowacki 1992, Tift and Fajvan 1999). Compared with the other residual trees, red maples had the lowest mean diameter but the second greatest basal area per acre. Unlike yellow-poplar and oaks, previously subdominant red maples can increase height and diameter growth following a crown release after a disturbance (Tift and Fajvan 1999). As the crowns of these trees expand, the understory will become more shaded, further inhibiting the growth of less shade-tolerant saplings (Fajvan and Wood 1996).

We expected that yellow-poplar size would show a stronger negative relationship with overstory basal area. Field observations indicated that most yellow-poplar saplings were located near yellow-poplar residual trees. Because these residuals typically had the smallest crowns sampled, saplings growing near them may have received enough light to remain vigorous. Yellow-poplar has rapid height growth rates in high light conditions (Olson 1969, Trimble 1973b, Lamson and Smith 1978) compared with associated species (Tift and Fajvan 1999). Even with an adequate seed source (yellow-poplar composed 50% of the basal area before harvest and 33% post-harvest), preferential browsing by white-tailed deer, observed for several years right after harvest, probably reduced the abundance and size of the saplings.

In a study that examined regeneration occurring in harvested stands with low residual basal areas (Miller et al. 2006), total height and diameter of dominant and codominant sapling reproduction increased with distance from residual overstory trees. The highest sapling basal area of shade-intolerant and midtolerant sapling species was found in open areas between residual tree crowns. These harvests left large, uniformly spaced residual trees with residual basal areas less than 30 ft^2/ac. Alternatively, Ray et al. (1999) found that the retention of widely spaced trees in shelterwood seed cuts did not affect new cohort development for at least 20 years. In our study, diameter-limit cutting resulted in irregular stand structures with no pattern in the distribution of openings and clusters of residual trees (Grushecky and Fajvan 1999). Therefore, it was difficult to isolate

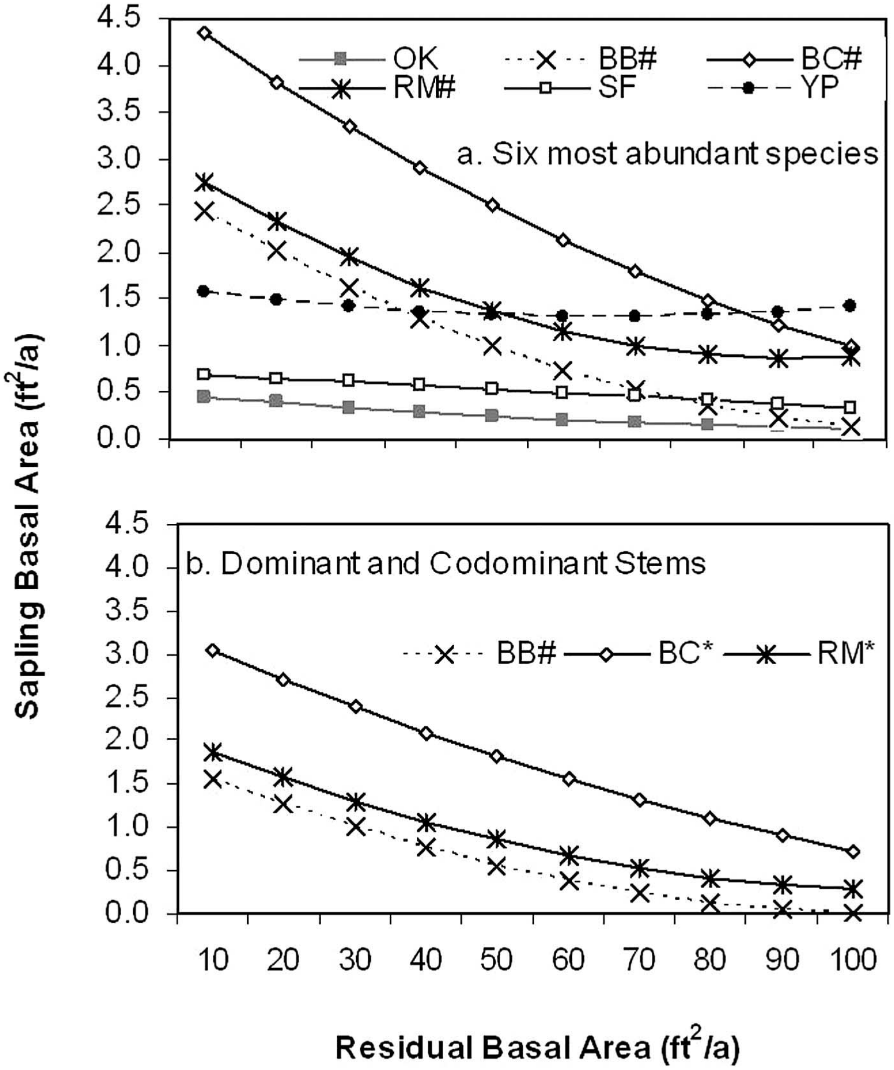

Figure 4. Sapling basal area profiles resulting from modeling basal area as a polynomial function of residual stand basal area. An asterisk (*) delineates a significant ($P < 0.05$) linear relationship and a pound sign (#) delineates a significant quadratic one. Sapling basal areas were log transformed before analysis. Graphs depict the relative effects of residual trees on sapling basal area of different species and crown class. BC, black cherry; BB, black birch; OK, red/black oak; RM, red maple; SF, sassafras; and YP, yellow-poplar.

the effects of individual residual trees on sapling development, largely because of the potential influence of other nearby residuals.

Our findings generally showed that 10 years after harvest, sapling height, dbh, and basal area were inversely related to degree of "overtopping" from residual trees. Red maple sapling height was not affected and the diameter showed a positive relationship with increasing overstory basal area. However, when analyzing only dominant and codominant red maple saplings, we found fewer significant differences because the shade-intolerant species had a greater representation in dominant and codominant crown classes. This crown stratification pattern is common at this early stage of stand development in Appalachian hardwoods (sensu Oliver and Larson 1996, Brashears et al. 2004).

Management Implications

Our findings indicated that 10 years after diameter-limit cutting, overall stand conditions were most favorable for the development of shade-tolerant species, with shade-intolerant ones developing well in the open areas. However, the long-term development of the abundant black cherry may be jeopardized by side shade and canopy cover. Stand rehabilitation in this situation requires removal of residual trees and subsequent reduction of sapling density to increase growth rates of the new cohort (Clatterbuck 2006). There are sufficient numbers of yellow-poplar and black cherry saplings for full site utilization, so cleanings can also be applied along with the liberation treatment.

In stands younger than 10 years old, the effects of cleaning have inconsistent results on growth rate of yellow-poplar (Trimble 1973b, Lamson and Smith 1978). Also, attempts to stimulate the growth of intermediate and overtopped black cherry have not been successful (Trimble 1973b). However, cleaning treatments targeting only dominant and codominant stems of yellow-poplar, black cherry, and oaks in stands more than 10 years old have resulted in their increased growth (Miller 2000).

For landowners to consider the expense of intensive cleaning treatments, there should be some guarantee of a future financial return. In our study, there were 323, 47, and 107 dominant and codominant stems per acre of black cherry, yellow-poplar, and red maple, respectively. Their average heights were slightly less than expected for similar trees on this site index (Miller 2000). Ensuring the recruitment of 60–70 stems/ac into eventual overstory canopy positions would be adequate to meet most management goals (Miller et al. 2007).

Cleaning treatments could also be used to increase survival and enhance the development of the larger oak stems. Of the 126 oaks/ac sampled, there were only about 11 codominant oaks. Selective browsing of oak seedlings that regenerated from the 1993 acorn crop most likely depressed height growth of many saplings. Data on growth rates of oaks released from subordinate crown class positions are inconclusive (Ward 1995).

In even-aged stands, diameter-limit harvesting can provide high initial financial returns (Reed et al. 1986, Erickson et al. 1990) because removals frequently target high-value species (Fajvan et al. 1998) and stem quality (Filip 1967). However, the residual stand will consist of many unmerchantable stems (Germain et al. 2007) that were previously in weak codominant, intermediate, or overtopped canopy positions; logging damage to these stems can be extensive (Fajvan and Knipling 2002). Hence, these stems are prone to vigor loss, epicormic sprouting (Trimble and Seegrist 1973, Erdman et al. 1985), and high mortality rates (Casperson 2006). Because of factors like these, long-term sawtimber yields after diameter-limit cutting can be as much as 30% lower when compared with stands managed with planned silvicultural treatments (Nyland 2002). Our evaluation of sapling regeneration development 10 years after diameter-limit cutting suggests that the abundant shade-intolerant black cherry will decline unless competition from residual trees is reduced. We recommend that the residual overstory trees be removed, and the stand be reevaluated for a subsequent cleaning operation to release desirable saplings.

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