

Fifty years of partial harvesting in a mixed mesophytic forest: composition and productivity

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Abstract: Long-term silvicultural trials contribute to sustainable forest management by providing a better scientific understanding of how forest ecosystems respond to periodic timber harvesting. In this study, species composition, diversity, and net periodic growth of tree species in a mixed mesophytic forest in the central Appalachians were evaluated after about a half century of management. Three partial cutting practices on 18 research compartments and on 3 unmanaged reference compartments were evaluated (1951–2001) on 280 ha. Single-tree selection, diameter-limit harvesting, and timber harvesting in 0.162-ha patches were assessed on three northern red oak site index₅₀ (SI) classes: 24, 21, and 18. Shannon–Weiner's diversity index (H') declined from the first (1951–1959) to last (1987–2001) measurements and was related to both SI ($P = 0.004$) and treatment ($P = 0.009$). Sugar maple (*Acer saccharum* Marsh.) and red maple (*Acer rubrum* L.) were the two most abundant species in recent years (1987–2001); in contrast, in initial inventories (1951–1959), northern red oak (*Quercus rubra* L.) and chestnut oak (*Quercus prinus* L.) were most abundant. Net periodic annual increment (PAI) of merchantable trees (DBH ≥ 12.7 cm) was related to both SI ($P = 0.004$) and treatment ($P = 0.003$). Mean PAI ranged from 4.6 m³·ha⁻¹·year⁻¹ for single-tree selection to 2.5 m³·ha⁻¹·year⁻¹ for unmanaged reference areas across all SI classes. The decline of oak species suggests that only intensive and specific forest management focused on maintaining oak species can obtain historical levels of diversity.

Résumé : Les expériences sylvicoles à long terme contribuent à l'aménagement forestier durable en procurant une meilleure compréhension scientifique de la façon dont les écosystèmes forestiers réagissent à une récolte périodique de matière ligneuse. Dans cet article, la composition en espèces, la diversité et la croissance périodique nette des espèces arborescentes dans une forêt mésique mixte de la zone centrale des Appalaches ont été évaluées après un demi-siècle d'aménagement. Trois méthodes de coupe partielle dans 18 compartiments expérimentaux et trois compartiments témoins non aménagés ont été évalués (1951–2001) sur une superficie de 280 ha. La coupe de jardinage par pied d'arbre, la coupe à diamètre limite et la coupe par trouées de 0,162 ha ont été évaluées pour trois classes d'indice₅₀ de station du chêne rouge : 24, 21 et 18. L'indice de diversité de Shannon–Weiner (H') a diminué du premier (1951–1959) au dernier (1987–2001) inventaire et était relié à la fois à l'indice de station ($P = 0,004$) et au traitement ($P = 0,009$). L'érable à sucre (*Acer saccharum* Marsh.) et l'érable rouge (*Acer rubrum* L.) étaient les deux espèces les plus abondantes au cours des dernières années (1987–2001), alors que le chêne rouge (*Quercus rubra* L.) et le chêne châtaignier (*Quercus prinus* L.) étaient les espèces les plus abondantes lors des premiers inventaires (1951–1959). L'accroissement périodique net des tiges marchandes (dhp $\geq 12,7$ cm) était relié à la fois à l'indice de station ($P = 0,004$) et au traitement ($P = 0,003$). L'accroissement périodique moyen pour l'ensemble des catégories d'indice de station variait de 4,6 m³·ha⁻¹·an⁻¹ dans le cas du jardinage par pied d'arbre à 2,5 m³·ha⁻¹·an⁻¹ dans les compartiments témoins non aménagés. La disparition des espèces de chênes montre que seul un aménagement forestier intensif et spécifique qui met l'accent sur le maintien des espèces de chênes peut atteindre des niveaux historiques de diversité.

[Traduit par la Rédaction]

Introduction

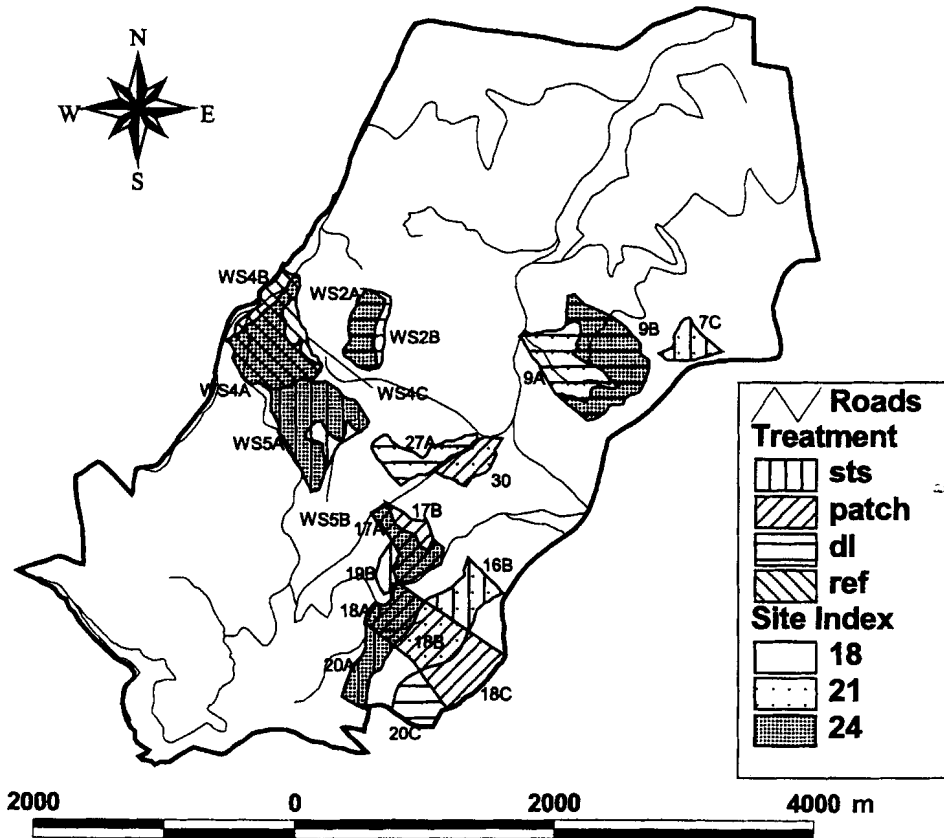
Partial harvesting is currently the dominant form of timber harvesting in central Appalachian forests (Fajvan et al. 1998). Most of the owners of nonindustrial private forest land who choose partial cutting are motivated more by the desire to harvest commercially valuable timber than by the desire to develop the future stand through silvicultural planning (Nyland 1992). Selective cutting that removes only large-diameter trees, often called diameter-limit harvesting,

is thought to degrade product yields through time (Nyland 1996). However, partial harvesting allows the landowner to maintain a continuous forest cover. In the central Appalachians, single-tree selection (Lamson and Smith 1991) and the more common diameter-limit harvesting (Fajvan et al. 1998) favor a preponderance of shade-tolerant species (Smith and Miller 1987; Schuler and Gillespie 2000). This often results in less oak (*Quercus* L.), yellow-poplar (*Liriodendron tulipifera* L.), and black cherry (*Prunus serotina* Ehrh.) and more maple (*Acer* L.), American beech (*Fagus grandifolia* Ehrh.), and American basswood (*Tilia americana* L.). Oaks are important commercially for sawtimber and veneer, and the associated hard mast production provides an important winter food source for a multitude of species (Wentworth et al. 1992; Wolff 1996). Shade-intolerant black cherry is important to many landowners because it has the greatest commercial value of any species in the region.

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Fig. 1. Locations of study compartments in the Fernow Experimental Forest by SI class and treatment. Note: dl, diameter-limit harvesting; patch, patch cutting; ref, unmanaged reference stands; SI, site index₅₀; sts, single-tree selection.



When this study was initiated, in 1950, stands were predominantly even aged and 38–45 years old, with variable densities of old-growth residual trees. Species composition was complex (Table A1) and varied with site (aspect, slope position, soil characteristics) and disturbance history, but it has generally been described as mixed mesophytic (Braun 1950), with northern red oak (*Quercus rubra* L.) and sugar maple more common on the relatively mesic sites, such as coves and north-facing slopes; and chestnut oak (*Quercus prinus* L.) and red maple (*Acer rubrum* L.) more common on the relatively xeric sites, such as ridge tops and south-facing slopes. Soils of the Fernow are predominantly of the Belmont and Calvin series (Losche and Beverage 1967). The Belmont soils are derived from Greenbrier Limestone, along with some sandstones and shales. The Calvin soils are derived from sandstone and shale and are more acidic and less fertile than the Belmont soils. Both are well-drained, medium-textured loams and silt loams, with an average depth of about 1 m. Understory vegetation is species rich and is dependent on site and disturbance history (Gilliam et al. 1995). Chestnut blight caused by *Cryphonectria parasitica* (Murr.) Barr, first noted in West Virginia as early as 1909, resulted in a 25% reduction in the volume of standing timber on the Fernow during the 1930s (Weitzman 1949).

Data collection

Field inventories were conducted for all trees more than 12.7 cm in diameter at breast height (DBH) by 5.08-cm classes and species before the first cut and usually just before each management intervention cycle (e.g., 10, 15, or

20 years thereafter) (Table 2). Smaller trees were not sampled systematically, because natural regeneration was not a formal study objective. Also, it was assumed that ingrowth into the smallest diameter class would eventually characterize the successful tree regeneration. Each tree was recorded as merchantable, cull (unmerchantable), or dead. Most cull material was cut during the first or second stand intervention and is no longer prominent in the managed compartments. The first inventories and assigned treatments were started in 1951 (Tables 1 and 2). The first phase of inventories and (or) treatments was completed by 1959 on all 21 compartments. Since the study was initiated the compartments assigned to this study have been manipulated according to the guidelines of the study only. All marked trees were tallied at each intervention, and residual stand structure following logging was calculated from the initial or recruise information less the species and diameter of trees removed. Logging crews made separate tallies of all trees not marked for cut that were damaged and cut during timber harvesting. Cubic volume estimates used in this analysis were developed from local volume tables derived from sites throughout the Fernow. In the 1950s, volume tables were constructed for each compartment. In 1971, the original data were used to revise the cubic volume tables for SI and species. The cubic volume of each tree ≥ 12.7 cm in DBH to a minimum top diameter of 10.2 cm was determined, and all volumes presented in this study are based on the 1971 revisions. Periodically, and most recently in 2002, volume tables were checked for validity; they continue to serve as useful estimators of actual tree volume. Because cubic volume in English

the results probably were not due to chance ($P = 0.020$), a three-dimensional solution was chosen for the final iterative ordination; the best ending point in the preliminary analysis was used as the starting point in the final run. Coefficients of determination (R^2) for each ordination axis were calculated as a proportion of the variation explained in the reduced matrix relative to that in the original matrix. Unlike other ordination techniques, NMS axis order does not correlate with the relative strength of the axis.

Univariate analysis of variance was used to discern differences in mean PAI related to treatments and SI. Both treatment and site classification were considered fixed effects. Model adequacy was evaluated using graphical and statistical techniques, including the Shapiro–Wilkes statistic, which tests the expected normality of the error component. Residuals were also plotted against both the predicted values and the independent variables to verify the assumption of constant variance. PAI means for each SI class and silvicultural treatment were plotted to expose significant interactions.

Repeated measures analyses were used to evaluate changes in productivity and diversity through time. Because management–measurement cycles differed somewhat across treatments (Table 2), the effects of time on PAI were evaluated separately for each treatment. To achieve adequate replication for a repeated measures analysis, data from SI classes 21 and 24 were combined after preliminary analysis indicated no significant differences in overall productivity, similar species composition, and equal cutting cycles (SI 18 cutting cycles were longer). Greater experimental replication may have permitted statistical differentiation between SI 21 and SI 24 compartments. Therefore, the results of the combined repeated measures analysis of these two SI classes should be interpreted with this mind. For patch cutting and single-tree selection, only compartments with five inventory cycles (40 years total) were used. This provided four repeated estimates of productivity ($n = 3$ compartments for each silvicultural treatment with five inventory cycles). For diameter-limit cutting, only compartments with four inventory cycles (45 years total) were used. This provided three repeated estimates of productivity ($n = 3$ compartments). Data from SI 18 compartments were not evaluated, because of insufficient replication for a repeated measures analysis. Temporal changes in measures of diversity (H' , J' , and species richness) from the initial to the most recent conditions were evaluated by repeated measure analysis, but somewhat differently than for PAI. Results from all compartments were combined using the first and last calculations of diversity. Site index₅₀ (height of the tallest trees at age 50), silvicultural treatment, time, and all potential interactions were considered fixed effects. To eliminate different inventory cycles and numbers of inventories, only the first (1951–1959) and most recent (1987–2001) inventories were used.

Results

Species composition and diversity

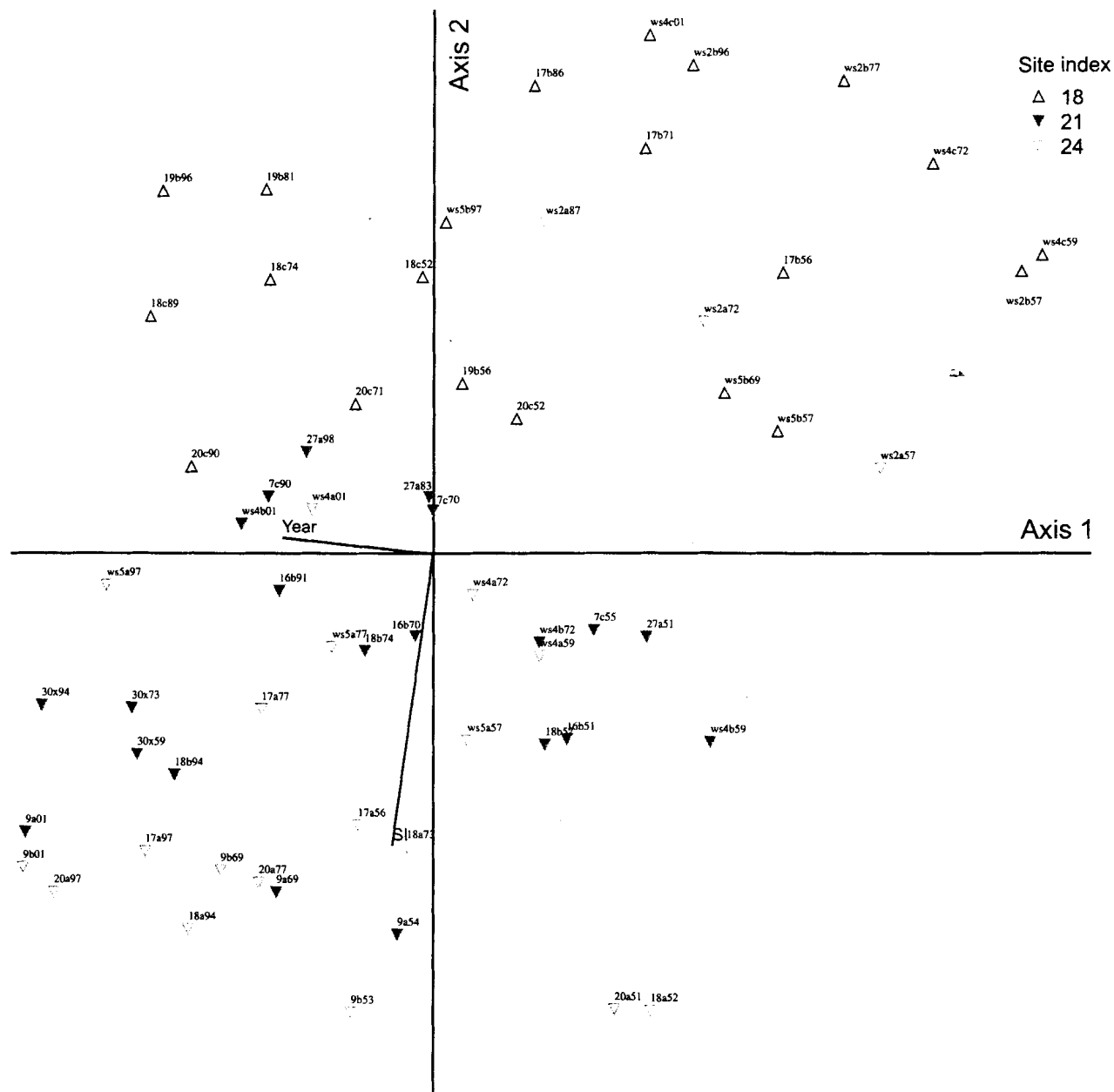
Thirty-two species of trees were identified during inventory dates in the period 1951–2001 within the study area (Table A1). During the most recent inventories, sugar maple and red maple were the two most abundant species, as measured by relative density. This was a notable change from

the initial inventories, when northern red oak and chestnut oak were the most abundant species. Northern red oak and chestnut oak declined to the third and eighth most abundant species, respectively. Apart from the maples, only American beech and black birch (*Betula lenta* L.) increased in importance: they represented at least 5% of overall relative density at the most recent inventory dates. All other species declined or were minor components of species composition.

There have been significant changes in compartment-level measures of diversity throughout this study, according to the first and last inventories. These changes were related to both SI and silvicultural treatment. In the repeated measures analysis of H' , both time \times SI ($P = 0.004$) and time \times treatment ($P = 0.009$) interactions were significant. Unmanaged reference and single-tree selection compartments were most notable with respect to declining diversity, and both differed significantly from initial conditions (Fig. 2a). Regardless of treatment, SI classes 21 and 24 were more diverse than SI 18 compartments when the study was initiated. However, through time, these classes (SI 21 and SI 24) have declined in diversity, while SI 18 has not (Fig. 2b). As a result, H' no longer differs across SI classes when compared using the Tukey–Kramer mean comparison procedure. The time \times treatment interaction was also significant ($P = 0.005$) when species richness was assessed, and this partially explains the reduction in H' . In the unmanaged reference areas, species richness declined significantly ($P = 0.020$, with the Tukey–Kramer mean comparison procedure) from a mean of 21.33 during the first inventory cycle to 19.0 most recently. In the analysis of evenness through time, J' was significantly related to the time \times SI interaction ($P = 0.016$). Evenness did not change appreciably on SI 18 compartments ($P = 0.635$), but it did decline on SI 21 ($P = 0.001$) and SI 24 ($P < 0.001$). Consequently, the decline in H' was due to the reduction in evenness for these SI classes.

Additional understanding of how overstory communities have changed through time was reflected in the NMS ordination. The proportion of variance explained in the final three-dimensional ordination was 23.7% for axis 1, 28.9% for axis 2, and 40.3% for axis 3 (cumulative $R^2 = 92.9\%$), indicating compartments were well separated in species space of the ordination. The first-ordination axis represented temporal change and was negatively correlated with the year of inventory ($r = -0.545$) when assessed from a secondary matrix. Northern red oak, white oak (*Quercus alba* L.), chestnut oak, and scarlet oak (*Quercus coccinea* Muenchh.) were positively correlated with axis 1 (i.e., they were less abundant through time) (Table 3). Conversely, sugar maple, yellow birch (*Betula alleghaniensis* Britton), black birch, and American beech were all negatively correlated with axis 1 (i.e., they were more abundant through time). Compartments along the second-ordination axis represented a gradient of species associations related to moisture and were negatively correlated with abundance of mesic species, such as sugar maple, black cherry, and yellow-poplar, and positively correlated with more xeric-tolerant species, such as red maple and chestnut oak (Table 3). Compartment SI had a strong negative correlation with NMS axis 2 ($r = -0.755$) when evaluated from a secondary matrix (Fig. 3). The third-ordination axis was positively correlated with H' ($r = 0.399$) and negatively correlated with SI ($r = -0.438$) and PAI ($r = -0.327$)

Fig. 3. Nonmetric multidimensional scaling ordination (axes 1 and 2) of research compartments grouped by SI class. Points are identified by compartment number and year of observation. Vectors radiating from the center of the ordination graph indicate the correlation of SI with axis 2 ($r = -0.755$); and year of observation, with axis 1 ($r = -0.545$). Species correlations with axis scores are in Table 3. Note: SI, site index₅₀.



$P_{[\text{patch}]} = 0.143$, $P_{[\text{ref}]} = 0.149$, where sts refers to single-tree selection; patch refers to patch cutting; and ref refers to unmanaged reference stands).

Discussion

In this study, temporal shifts in species composition corroborate local and regional forest trends, which indicate a decline in all oaks and hickories (*Carya* Nutt. spp.) and an increase in red and sugar maples (Parker et al. 1985; Abrams and Downs 1990; Schuler and Gillespie 2000). This trend is often accompanied by a concomitant decline in diversity. In terms of forest management options, this decline in oak and sympatric species has been partially offset for several de-

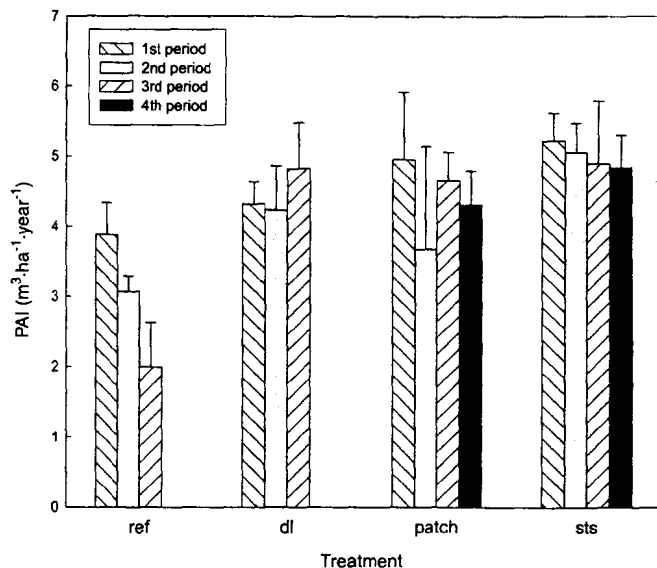
cadecades because of abundant oaks in smaller size classes that were recruited into the commercial classes as canopy dominants were harvested periodically. For example, before treatment began in 1954, there were more than 350 red and chestnut oaks in the 15-cm DBH class alone in compartment 9a (one compartment of the diameter-limit treatment). By 2001, there were fewer than 50 oak stems in the same size class, or about 2 oaks·ha⁻¹. Based on the probability of virtually no new recruitment and the expected diameter growth rate of about 5 cm·decade⁻¹ (Lamson and Smith 1991), all of the remaining oak will be harvested in about 50–60 years, according to the 43-cm DBH diameter-limit protocol used in this study. Smaller minimum diameters (e.g., 30 cm), often used in commercial logging operations, would shorten this

Table 4. Cubic volume net PAI of merchantable trees (DBH ≥ 12.7 cm).

Treatment and SI category	Mean PAI ($\text{m}^3\text{-ha}^{-1}\text{-year}^{-1}$)	N
Single-tree selection	4.55a	6
Diameter-limit harvesting	4.28a	6
Patch cutting	4.00a	6
Reference (unmanaged)	2.52b	3
SI 24	4.46a	7
SI 21	3.98ab	7
SI 18	3.64b	7

Note: Treatment means from about 1951 to 2001 for each treatment and SI class. Means separated ($\alpha = 0.05$) using the Duncan mean comparison procedure and designated by lower case letters. DBH, diameter at breast height; PAI, periodic annual increment; SI, site index₅₀.

Fig. 5. Mean cubic volume net PAI of merchantable trees (DBH 12.7 cm) (vertical lines = 1 SE) by measurement cycle and treatment category (northern red oak classes SI 21 and SI 24). Compartments 27a, 9a, and 9b included in dl; 16b, ws5a, and 20a included in sts; ws4a and ws4b included in ref; and 30, 18a, and 18b included in patch. Measurement cycles differed by treatment and were as follows: 10 years for sts and patch; 15 years for dl; and 10, 20 and 40 years after the initial inventories for the reference compartments. Note: DBH, diameter at breast height; dl, diameter-limit harvesting; PAI, periodic annual increment; patch, patch cutting; ref, unmanaged reference stands; sts, single-tree selection.



this study. Beech bark disease, caused by an exotic beech scale (*Cryptococcus fagisuga* Lind.) and necrotic fungi (*Nectria coccinea* var. *faginata* Lohm., Wats., & Ayers and *Nectria galligena* Bres.) association (Houston and O'Brien 1983), is beginning to cause overstory mortality of American beech in the immediate vicinity of the Fernow Experimental Forest. Thus, a transition to a beech-maple-basswood forest probably will lack overstory beech and associated production of hard mast. The expected future composition represents a significant change from the previous mixed mesophytic forest type, which included hard mast

from oaks, hickories, beech, and—at one time—American chestnut, as well as other species of lesser importance, e.g., black walnut (*Juglans nigra* L.) and butternut (*Juglans cinerea* L.). As stated earlier, mast-producing species are a critical food source for many wildlife species, particularly in the winter (Wolff 1996; McShea 2000). Eastern hemlock (*Tsuga canadensis* (L.) Carr.) is also expected to be affected by new forest pathogens. A minor component of the study area but long present, eastern hemlock may be functionally extirpated because of the exotic hemlock woolly adelgid (*Adelges tsugae* Annand), which has spread to the Allegheny Mountains (USDA Forest Service 2002). Eastern hemlock is considered a constituent of late successional forest in the region (Smith 1995) and is often found in ecologically important riparian corridors.

A conversion in forest type from mixed mesophytic to beech-maple-basswood, even absent forest health problems, would be unprecedented during Middle to Late Holocene in the central Appalachians. Such a change could not be attributed to successional change only. Extensive pollen studies have revealed patterns of persistence of mesic oak communities in the eastern hardwood forests for several thousand years (Delcourt and Delcourt 1987). Holocene vegetation dynamics determined from pollen analysis reveal dramatic changes in species composition during the period 17 000 – 8 000 years BP as the global climate warmed. However, for the last 8000 years, upland forests in the Allegheny Mountains have been dominated by oak, birch, and chestnut (Larabee 1986). During the last 2000 years and before European settlement, oak made up about 60% of the forest composition in the central Appalachians (Delcourt and Delcourt 1987). During this time, Native American use of fire may have created conditions suitable for oak to compete successfully with both early and late seral species (Whitney 1994; Delcourt and Delcourt 1997). Following settlement, oaks and other mid-seral species may have been further enhanced by repeated partial cuttings, fires, and the decline of American chestnut (Whitney 1987; Crow 1988; Abrams et al. 1995). A recent dendroecological study found that oak, using growth strategies appropriate to both large and small openings (<200 m²), became established in remnant old-growth forests in the central Appalachians until recruitment ceased in the early 20th century (Rentch et al., 2003).

If diverse stands are a management objective for statutory or ecological reasons, this study demonstrated that stand-level diversity is declining in forests managed with single-tree selection and diameter-limit harvesting. However, there is no evidence that these practices are accelerating this process relative to unmanaged stands. In this study, unmanaged and single-tree selection compartments exhibited the greatest decline in diversity (H') as shade-tolerant species increased in relative density. Perhaps only the patch cut compartments would provide canopy gaps large enough to avoid the trend of increasing dominance of shade-tolerant species. In earlier work focusing on the species composition of the patches, shade-intolerant yellow-poplar, black cherry, and black locust (*Robinia pseudoacacia* L.) were able to compete with shade-tolerant species in the patch openings two decades after the patches were created (Miller et al. 1995). These results also demonstrated that light was adequate for oak development. However, unless understory density is con-

central Appalachians (Fajvan et al. 1998). Woodland owners continue to prefer this method because it often maximizes short-term cash flow and is easy to apply (Miller 1993). A diameter-limit technique that incorporates economic guidelines, controls residual stem quality, and manages residual stocking has been suggested as a less complicated alternative to single-tree selection (Miller and Smith 1993). However, no known treatment can avoid problematic changes in species composition associated with this type of management.

Sustainable forest management includes maintaining long-term forest productivity by balancing wood removals with what is determined to be sustainable (Montreal Process Criterion and Indicators 1998). Determination of what has been removed is straightforward, but estimating potential long-term forest productivity is complex (Powers et al. 1994). Potential threats to sustainable forest productivity in the central Appalachians include long-term acidic deposition and the impacts of repeated harvesting on nutrient depletion (Adams et al. 2000). In some cases, the effects of timber harvesting have been assessed indirectly by measuring soil nutrients before and after management activity (Hendrickson et al. 1989; Kraske and Fernandez 1993), but the results are influenced by the addition of new biomass to the forest floor, which can increase soil nutrient availability in the short term (Knoepp and Swank 1997). Chronic acidic deposition can also reduce site productivity by reducing soil base cation availability (Adams 1999). The unmanaged reference stands in this study have been monitored intensively for the effects of acid deposition. Signs of nitrogen saturation have been reported, but the effects on periodic growth are unknown (Adams 1999). Current growth rates are less in these unmanaged reference stands than in managed areas, but presumably this difference is primarily related to stocking and increasing stand age and reflects the difficulty of assessing long-term potential productivity. By ultimately achieving stability with respect to stocking and composition, long-term silvicultural trials provide opportunities to periodically measure productivity and assess long-term trends in a changing environment. Through these assessments, determination of the level of sustainable forest production may be possible.

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Appendix A

Table A1. Relative stem density and current rank of woody overstory species from most recent, middle, and oldest inventory dates.

Species	Current rank	1987–2001	1970–1981	1951–1959
<i>Acer saccharum</i>	1.000	0.197	0.131	0.069
<i>Acer rubrum</i>	2.000	0.161	0.122	0.078
<i>Quercus rubra</i>	3.000	0.136	0.180	0.198
<i>Fagus grandifolia</i>	4.000	0.070	0.048	0.044
<i>Betula lenta</i>	5.000	0.065	0.062	0.060
<i>Quercus prinus</i>	6.000	0.059	0.077	0.082
<i>Liriodendron tulipifera</i>	7.000	0.055	0.052	0.059
<i>Prunus serotina</i>	8.000	0.047	0.054	0.079
<i>Tilia americana</i>	9.000	0.043	0.042	0.038
<i>Magnolia fraseri</i>	10.000	0.025	0.027	0.031
<i>Magnolia acuminata</i>	11.000	0.021	0.026	0.026
<i>Fraxinus americana</i>	12.000	0.021	0.030	0.032
<i>Quercus alba</i>	13.000	0.014	0.018	0.019
<i>Betula alleghaniensis</i>	14.000	0.012	0.012	0.012
<i>Tsuga canadensis</i>	15.000	0.009	0.004	0.001
<i>Carya cordiformis</i>	16.000	0.009	0.018	0.030
<i>Robinia pseudoacacia</i>	17.000	0.008	0.016	0.047
<i>Oxydendrum arboretum</i>	18.000	0.007	0.013	0.013
<i>Ostrya virginiana</i>	19.000	0.007	0.005	0.003
<i>Amelanchier arborea</i>	20.000	0.006	0.006	0.003
<i>Sassafras albidum</i>	21.000	0.005	0.026	0.048
<i>Prunus pensylvanica</i>	22.000	0.005	0.004	0.000
<i>Nyssa sylvatica</i>	23.000	0.005	0.007	0.011
<i>Quercus coccinea</i>	24.000	0.005	0.006	0.000
<i>Carya ovata</i>	25.000	0.003	0.009	0.008
<i>Ulmus rubra</i>	26.000	0.002	0.001	0.002
<i>Quercus velutina</i>	27.000	0.000	0.001	0.000
<i>Juglans cinerea</i>	28.000	0.000	0.000	0.003
<i>Populus grandidentata</i>	29.000	0.000	0.001	0.003
<i>Cornus florida</i>	30.000	0.000	0.000	0.001
<i>Juglans nigra</i>	31.000	0.000	0.000	<0.001
<i>Picea rubra</i>	32.000	0.000	0.000	<0.001

Note: Observations are combined for all treatments to illustrate overall temporal trends (including unmanaged reference stands).