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Managing Appalachian hardwood stands using four management practices: 60-year results ☆

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ABSTRACT

A long-term forest management case study on the Fernow Experimental Forest in West Virginia referred to as the Cutting Practice Level study is evaluated after 60 years. Treatments include a commercial clearcut (one time application), a 39 cm diameter-limit (applied 4 times), uneven-aged management using two variations of single-tree selection (applied 7 and 8 times, respectively), and an unmanaged reference area. We examine productivity, species composition and diversity, structure, tree quality, and revenues generated related to each treatment since establishment. The diameter-limit treatment resulted in greatest average periodic annual increment (PAI) of sawtimber volume of 3.1 $m^3\ ha^{-1}\ yr^{-1}$ while the unmanaged reference area resulted in the least of 2.2 $m^3\ ha^{-1}\ yr^{-1}$ (based on the difference in standing volume from 1956 to 2008). All types of partial harvesting resulted in greater sawtimber productivity than either the commercial clearcut or the reference area. Post-harvest tree quality, as measured by proportion of grade 1 butt logs, has improved from 1988 to 2008 for all but the diameter-limit treatment, which is similar to conditions in 1968. In 2008, the proportion of grade 1 trees in the residual stand ranged from a high of 0.22 for single-tree selection to 0.15 for diameter-limit harvesting. Species composition is becoming less diverse and more dominated by shade-tolerant species in all treatment groups but the change has been the greatest in the two single-tree selection treatments. Initially, size-class distributions were somewhat unimodal and reflective of even-aged stands with shade tolerant species persisting in the understory. In 2008, the single-tree selection treatments were both characterized by a reverse-J size class distribution and it appears this structure can be maintained due to recruitment of shade-tolerant species in the smaller size classes with concomitant reductions in species diversity. The net present value for each treatment in 2008, the time of the last management intervention, ranged from \$20,000 ha^{-1} for reference area to almost \$34,000 ha^{-1} for the single-tree selection treatment that included management of pole-sized trees based on all revenue and the value of standing timber using an internal rate of return of 4%.

1. Introduction

In the middle of the 20th century, forest science was still in its early developmental phase in North America. Following a period of forest exploitation from about 1880–1920 in the eastern United States and the end of World War II, scientists and managers were poised to test and apply concepts about forest management that were not yet fully understood. Long-term forest research and demonstrations were set up on the network of Experimental Forests administered by the U.S. Forest Service to learn more about silviculture, economics, utilization and other issues (Shapiro, 2014). Some of these studies and demonstrations continue to the present time and the insights gained are often contrary to the original hypotheses or expectations. Moreover, as time passes, what society wants or needs from forests also changes and likewise the questions asked about these long-term studies also change. Habitat for protected species, carbon sequestration and climate change resilience are all relevant issues today, but were not envisioned when these older silvicultural experiments were initiated. Thus, some of the most valuable insights gained from long-term silvicultural research may be unrelated to the original goals of the study.

Here we report on a silvicultural demonstration that spans more than six decades and highlights both the challenges and opportunities gained through long-term studies on experimental

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forests (Lugo et al., 2006; Hayes et al., 2014). In 1948 an area was established on the Fernow Experimental Forest in West Virginia to demonstrate different forest management practices that could be applied to hardwood forest types in the Central Appalachians. This descriptive case study, referred to as the Cutting Practice Level (CPL) demonstration, consisted of four compartments each assigned a different long-term management practice, including a commercial clearcut, a diameter-limit harvest, and two variations of single-tree selection. In 1956, an adjacent unmanaged area with the same site conditions and pretreatment disturbance history was added to serve as a reference condition through time. For the past 60 years, harvests have continued without interruption, approximately every 10 years for the single-tree selection compartments and every 20 years for the diameter-limit compartment.

The term "cutting practice levels" was first used in a 1945 survey of forest conditions and forest management being conducted throughout the United States (Harper and Rettie, 1946). At that time, the "levels" of high-order, good, fair and poor were intended to reflect the quality of forest management practices in use at that time. The same terminology was incorporated into the Fernow CPL demonstration as high-order (single-tree selection that included management of pole-sized trees and other additional treatments), good (single-tree selection for sawlog-size trees only), fair (diameter-limit harvesting), and poor (commercial clearcut) cutting practices. Other experimental forests in the northeast and north-central United States have similar case studies that were established at about the same time for the same purpose but treatments vary according to each region (Kenefic and Schuler, 2008).

The CPL case study on the Fernow began with a set of descriptive theories about how forests respond to different cutting practices. High-order cutting was considered the best method of harvesting that would rapidly build up and maintain the quantity and quality of yields consistent with the full productive capacity of the land. Good cutting was characterized as a practice that would produce acceptable yields and retain desirable species, although with longer cutting cycles than high-order cutting. Fair cutting was envisioned as a practice that would result in some species that were marketable with sufficient growing stock to yield a commercial harvest but require a longer cutting cycle than with high-order or good cutting practices, about every 20–30 years. And poor cutting was envisioned as a practice that would provide limited means for natural regeneration of desirable species following liquidation-style cutting resulting in forest decline; represented by short-lived and unmerchantable species and reduction in both quantity and quality of yield.

As a case study, the Fernow CPL was not designed to rigorously test these theories but to demonstrate this range of forest management practices. However, after 60 years of forest management research in the northeastern and north-central United States, most initial assumptions have been modified or rejected by the cumulative efforts of researchers region-wide and the results presented here, illustrating the importance of on-the-ground trials of accepted but untested forestry principles. The trends we report illustrate long-term forest stand dynamics and economic returns that were not anticipated decades ago and provide the opportunity for developing new ideas about forest stand dynamics and related concerns in the 21st century.

2. Methods

2.1. Study area

This case study was conducted on the Fernow Experimental Forest in north-central West Virginia (39.03°N, 79.67°W). The Fernow is part of the Allegheny Mountains of the Central Appalachian Broadleaf Forest (McNab and Avers, 1994). The average growing season is about 145 days and annual precipitation averages 142 cm (Pan et al., 1997). The CPL encompasses 5 equally-sized compartments totaling just over 10 ha with a predominantly western aspect. The relatively small area facilitated the training and demonstration component of this work. Larger areas on the Fernow that are replicated and with site index added as an explanatory variable have been reported on before and partially corroborate the findings we report on here (Schuler, 2004). The site has an average elevation of 760 m ASL with slopes ranging from 10 to 30% and an average northern red oak site index of about 24 m. The Belmont soils of the CPL study area have moderately high fertility and soil moisture capacity. Historically, the site has supported northern red oak (*Quercus rubra*), yellow-poplar (*Liriodendron tulipifera*), and sugar maple (*Acer saccharum*) and the forest type is classified as mixed-mesophytic. Collectively these features represent one of the most productive sites in the Central Appalachians.

2.2. Silvicultural treatments

The commercial clearcut (CC) in the CPL removed all merchantable stems greater than 12.7 cm dbh (diameter at breast height) after the 1949 growing season with no cull tree removal or planned silvicultural treatments to improve the next stand. This was presumed to be an exploitive type of harvest believed to be the "prevalent liquidation method of cutting characterized by forest deterioration" at the inception of this case study (Weitzmann, 1949). It was assigned the "poor" forest management practice moniker, but it was noted that at times it might be more appropriately classified as a destructive cutting practice. Although no intermediate treatments were planned, in 1988, 40 years after the regeneration harvest, grapevines (*Vitus* spp.) were cut so that the ongoing even-age stand development could progress. Approximately 825 vines were cut using hand tools and required 4.5 h of labor. This cultural treatment deviated somewhat from the original intent to represent only poor or exploitive practices for this part of the case study.

A diameter-limit harvest (DL) on a 20-year cutting cycle was implemented as a "fair cutting" practice. Since the first harvest in 1949, there have been three additional harvests in 1968, 1988, and 2008. In each harvest, all trees more than 39 cm dbh were cut while smaller trees were allowed to remain in the stand, reflecting the original "fair" level of management intensity. Also, most grapevines are cut near the ground line after each cutting cycle. Some small grape arbors, where grapevines developed into matted entanglements in tree crowns and cause periodic crown damage due to snow loading, have existed in this compartment for many years but were not allowed to expand by cutting vines around the perimeter of the arbor.

Single-tree harvesting of sawlog-size trees (ST) on a 10-year cutting cycle was used for the "good" cutting practice level. To date, there have been seven harvests (1949, 1958, 1968, 1978, 1988, 1998, and 2008) and in each one some trees more than 28 cm dbh and all grapevines were cut or girdled. Residual stand goals were defined by the BDq method (Nyland, 1996) which consists of the residual basal area (B), the dbh of the largest tree to retain after each harvest (D), and the ratio of trees in successively smaller size classes (q). The q-value results in a negative exponential size-class distribution, sometimes referred to as a reverse-J distribution. In this instance, the prescription included a residual basal area for sawlog-size trees of 16 $m^2\ ha^{-1}$, a maximum dbh of 81 cm, and a q of 1.3 (based on 5 cm dbh classes). The maximum dbh is appropriate for the excellent growing conditions found at the site.

Single-tree selection for pole- and sawlog-size trees (SP) was used for the "high-order" cutting practice. The residual stand structure goals were similar to the ST treatment, maximum dbh and the q-value remain the same, but minimum dbh for cutting and residual basal area were adjusted to 12.7 cm and 19.5 m^2 ha^{-1}, respectively to account for management of the pole-size trees. In the early years of this case study, the SP cutting cycle was planned for 5 years but the harvest volume was insufficient so the cutting cycle was put on the same 10-year schedule as ST. Thus, harvests have occurred in 1949, 1958, 1963, 1968, 1978, 1988, 1998, and 2008. In keeping with the intention to use a "high-order" management practice, there have been other silvicultural treatments prescribed as well. In the early years, tops of harvested trees were lopped to promote faster decay and enhance nutrient cycling. In 1959, about 50 small sugar maples (dbh from about 8–25 cm) were pruned to a height of about 5 m. In 1960, a weeding and a cleaning killed 318 "small worthless hardwoods" according to the study file using tree injection and mechanical means. The ST and SP treatment areas represent one of longest running examples of the BDq method of single-tree selection in the eastern United States.

Species preferences for both single-tree selection practices have evolved over the decades reflecting changing management priorities. Initially, when timber values were of preeminent concern, American beech (*Fagus grandifolia*) and hickory (*Carya* spp.) were targeted for removal due to their usual poor form and low commercial value. By 1998, species selection criteria were notably different. Shagbark hickory (*C. ovata*) was not marked for harvest, unless it posed a significant safety risk, because it was recognized as a preferred roost tree for the endangered Indiana bat (*Myotis sodalis*) (Menzel et al., 2001; Johnson et al., 2010). For the last two cutting cycles we also have chosen to favor northern red oak as a retention species, where feasible, due to its scarcity in the smaller size classes. From the beginning, trees of high quality were favored to retain in the stand over poor quality trees, regardless of species.

A reference area (REF) immediately adjacent to the treated areas was established in 1956 (Kenefic et al., 2005b). This area has similar site conditions and a pre-treatment disturbance history. The entire CPL area was first logged c. 1907 during the railroad logging era and forest fires burned over the area repeatedly prior to federal ownership in 1915 (Weitzmann, 1949; Schuler and Gillespie, 2000). Since then fire and grazing on these sites has been excluded and the tract was designated for research purposes in 1934.

2.3. Data collection and analysis

Periodic inventories have been done to monitor stand growth and yield, species composition, butt log grade and other parameters not included here. A 100% inventory of all overstory trees (dbh ⩾ 12.7 cm) using 5 cm dbh classes was made in each treatment area just prior to the 10-year harvest cycle in the single-tree selection treatments. Inventories and harvests were in the dormant season. This effort typically requires tallying about 3000 stems at each 10-year measurement. The butt log (approximately the first 5 m) of all harvested trees was graded when marked for selection using Forest Service tree grades for sawtimber (Rast et al., 1973). Plus, grade samples of all residual trees not harvested are based on dbh categories (±2.5 cm) as follows: 31 cm dbh - 1 in 15 trees sampled; 36 cm dbh - 1 in 8 sampled; 41 cm dbh – 1 in 4 sampled; 46 cm dbh - 1 in 2 sampled; and 51 cm dbh and greater – grade assessed for all trees. Merchantable volume estimates were based on board foot volumes (Int. ¼ in.) for sawlog-size trees to a 20 cm diameter inside bark top using local volume equations developed in 1971 based on site index, dbh, and species (on file at the Timber and Watershed Laboratory, Parsons, WV). Board foot volumes were converted to cubic volume (m^3 ha^{-1}) using a direct conversion and are thus conservative estimates of total volume. Net periodic annual increment (PAI) of merchantable trees (dbh ⩾ 28 cm) was computed as the difference in ending and initial measurements of merchantable volumes, plus any harvest volume that occurred at the beginning of the period, divided by the number of years within the inventory cycle. In 2008, since we only had the initial but not the ending volume, we simply used the harvest volume, if any, divided by the cutting cycle. This approach provided one more estimate of PAI for the ST, SP, and DL treatments. Dead and unmerchantable trees were not included in the productivity estimates. Mean annual increment (MAI) for the CC treatment was computed as the cumulative average annual PAI.

Stumpage revenues received from the sale of all wood products during the 60-year period were summarized and adjusted for present value. In all there were 20 revenue producing transactions. We calculated the net present value (NPV) of all revenue using an internal rate of return (IRR) of 4%. The timber was valued by the actual amounts paid by the stumpage buyer at each time period. The residuals in 2008 were based on stumpage rates paid at that time applied to the residual stand. As noted above, treatments also had variable levels of management inputs which included cultural treatments, marking, and logging. We lacked sufficient data to include expenses in our results but we did have notes regarding the number of cultural treatments and when they occurred. We used this information to modify our valuations and will address this issue in the discussion of our results.

Because this was implemented as a case study designed to demonstrate forest management practices and not test hypotheses, treatment units were not replicated and most inferential statistics are not relevant. However, we did use ordination to help describe species composition through time and treatment. Species composition analyses were based on relative importance values (IV) defined as the mean of relative basal area and relative density for each species and time period. We used IV to calculate the Shannon-Weiner diversity index (H′) (Whittaker, 1972) for each time period and management practice. We used nonmetric multidimensional scaling (NMS) using PC-ORD v6.0 (McCune and Mefford, 2011) based on the Sorensen distance measure with 50 runs of real data and 50 runs of randomized data for a Monte Carlo test of significance. Following a finding that the results were not due to chance (P = 0.0196), the best ending point in the preliminary ordination was used as the starting point in the final run (McCune et al., 2002). In our primary matrix we had 23 columns of species and 35 rows of species IV; in the secondary matrix we included H′ and year of observation as quantitative variables and cutting practice as a categorical variable.

3. Results

3.1. Productivity

From about 1960–1980, PAI trends among the treatments were similar and ranged from 1.9 to 3.3 m^3 ha^{-1} yr^{-1} (Fig. 1). However, in the 1990s, the CC and REF treatments diverged with productivity increasing in CC and decreasing in REF. PAI peaked at over 3.5 m^3 ha^{-1} yr^{-1} in the CC during the 1990s. This peak is predicated on a period of desirable stocking in even-aged stand development and occurred about 40–50 years after CC was harvested. Basal area ranged from 24.8 to 30.1 m^2 ha^{-1} (dbh ⩾ 12.7 cm) when PAI peaked. Productivity subsequently decreased in the CC treatment in the following decade and continued to decline in the REF area following expected age and stocking related even-aged stand dynamics. In 2008, MAI was still increasing in the CC treatment, but based on the current decline in PAI, it appears periodic productivity in

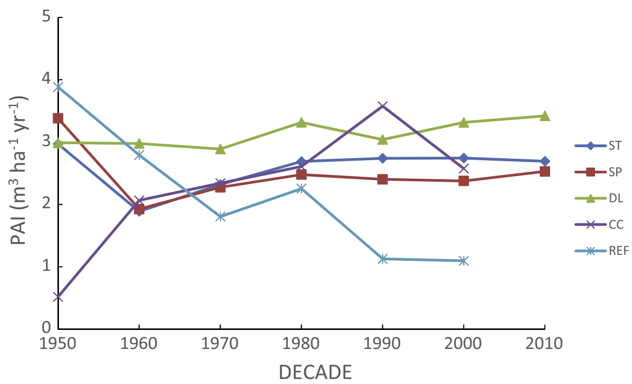

Fig. 1. Net periodic annual increment (PAI) of merchantable sawtimber (dbh > 28.0 cm) by decade and treatment. Cubic volumes were converted from board feet providing a conservative estimate of productivity (ST – single-tree selection for sawlog-size trees; SP – single tree selection for sawlog and pole-size trees; DL – diameter-limit; CC – commercial clearcut; REF – unmanaged reference area; modified from Schuler, 2014). Note: these levels are decadal averages based on difference between the beginning and ending measurements plus any harvest volume that may have occurred and dividing by the number of years in the period. PAI estimates for the 2010 period are based on harvest volume alone which is only feasible for ST, SP, and DL.

2018 will drop below MAI, resulting in the culmination of MAI at 2.3 m^3 ha^{-1} yr^{-1} 70 years after the last harvest. PAI in the unmanaged reference area was at or below 1.1 m^3 ha^{-1} yr^{-1} during the 1990 and 2000 measurement periods and basal area was 42.2 m^2 ha^{-1} at the last measurement period. In the two single-tree selection treatments (ST, SP) PAI was about 2.5 m^3 ha^{-1} yr^{-1} with similar levels of productivity since the 1980s. Management of pole-sized trees in the SP treatment did not change productivity from the ST treatment where only sawlog-size trees were managed. ST and SP basal area fluctuated from about 20 to 26 m^2 ha^{-1} over the past four decades. Unexpectedly, PAI for the DL treatment has remained above 3.0 m^3 ha^{-1} yr^{-1} for the past four decades and has been consistently greater than all other treatments since 1960 except when the CC treatment peaked about 1990. DL basal area has been about 12 m^2 ha^{-1} after harvesting and aggrading to about 24 m^2 ha^{-1} just before harvest during this time period.

Total harvested volume from the four treatments in this case study to date ranges from a low of about 60 m^3 ha^{-1} for the CC treatment to 233 m^3 ha^{-1} for DL based on 4 harvests and the 20-year cutting cycle (Fig. 2). The ST and SP treatments have yielded over 155 m^3 ha^{-1}. Adding residual standing volume in 2008 to the harvested volumes for the past 60 years provides an estimate of total net merchantable volume production. The diameter-limit treatment has resulted in greatest net production of over 250 m^3 ha^{-1} while the reference area has resulted in the least (183 m^3 ha^{-1}) (Fig. 2). All types of partial harvesting resulted in greater productivity than either the CC or REF treatments, both representative of even-age stand development beginning in 1949 and c. 1908, respectively. The difference in net wood production between the DL and REF treatments during the past 60 years was about 50 m^3 ha^{-1}, which is more than the average volume of wood present in the CPL area in 1948.

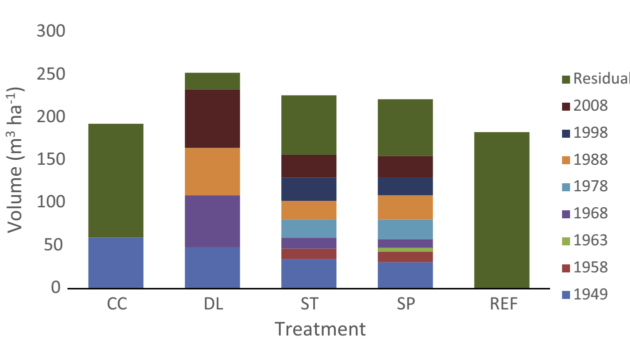

Fig. 2. Harvest volume for each treatment and time period combined with residual standing volume in 2008 (ST – single-tree selection for sawlog-size trees; SP – single tree selection for sawlog and pole-size trees; DL – diameter-limit; CC – commercial clearcut; REF – unmanaged reference area).

3.2. Grade

The proportion of harvested grade 1 butt logs has varied from a low of less than 0.05 in 1958 for ST to nearly 0.40 in 2008 for the SP treatment (Fig. 3A). The quality of harvested trees in SP and ST treatments has been improving for the last two cutting cycles. Coupled with increasing proportions of residual grade 1 butt logs in these two single-tree selection treatments (Fig. 3B), it appears this trend will continue. We also recorded improved tree quality in the CC and REF treatments. The CC treatment has improved the most in terms of grade 1 butt logs, likely because the percentage of trees of minimum size to be a grade 1 has increased from 43% in 1988 to 61% in 2008. Consistent with its original "fair" management designation, the DL treatment was designed to only harvest trees that were large enough to have grade 1 butt logs. In practice, it has yielded about 1 in 4 trees with a grade 1 butt log over the last three 20-year cutting cycles. It also has the lowest residual tree quality of all of the alternative management scenarios.

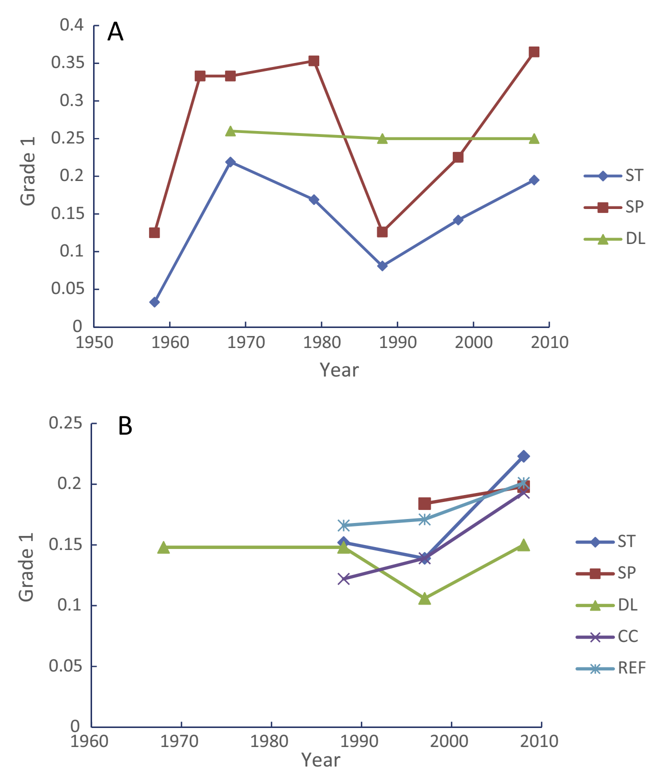

Fig. 3. Proportion of grade 1 trees marked for harvesting through time by treatment (A) and proportion of grade 1 trees in the treatment groups at each time interval (B) (ST – single-tree selection for sawlog-size trees; SP – single tree selection for sawlog and pole-size trees; DL – diameter-limit; CC – commercial clearcut; REF – unmanaged reference area).

3.3. Species composition and diversity

There were 23 species of trees (dbh greater than 12.7 cm) identified throughout the study area from 1948 to 2008. On average through time, the most common species in terms of relative IV were sugar maple (28%), yellow-poplar (26%), northern red oak (7%), black locust (*Robinia pseudoacacia*; 7%), white ash (*Fraxinus americana*; 5%), and black cherry (*Prunus serotina*; 5%). The most abundant 10 species constituted more than 93% of the relative importance value for the area studied. However, composition has changed as a function of both time and treatment as indicated by the NMS ordination (Fig. 4), which resulted in a final stress of 9.4 indicating a reliable solution (McCune and Mefford, 2011).

NMS axis-1 and axis-2 accounted for 56.8 and 37.4% of the variance in the preferred two-dimensional solution, respectively. Species composition was most unchanged through time in the REF area and the most dynamic in the ST and SP treatments as suggested graphically by the distribution of plots in ordination space (Fig. 4). Axis-1 was negatively associated with year of observation ($r = -0.365$) and positively associated with H′ ($r = 0.489$) and axis-2 was positively associated with year of observation ($r = 0.691$) and negatively associated with H′ ($r = -0.406$). In other words, species composition is becoming less diverse through time and is shifting to the upper-left quadrant of the ordination. Axis 1 was positively correlated with shade-intolerant species yellow-poplar ($r = 0.829$) and black locust ($r = 0.831$) and negatively correlated with shade-tolerant species sugar ($r = -0.838$) and red maple (*A. rubrum*; $r = -0.687$). Whereas, axis-2 was negatively correlated with hard mast producers bitternut (*C. cordiformis*; $r = -0.855$) and shagbark hickory ($r = -0.208$), American beech ($r = -0.714$) and white oak ($r = -0.669$) and most positively correlated with sugar maple ($r = 0.433$) and basswood ($r = 0.390$).

Despite the differences among the treatments, all of the treatments are becoming less diverse (Fig. 5A) and composed of more shade-tolerant species (Fig. 5B), although partial harvesting seemed to accelerate the process. Note that ten years after diameter-limit harvesting in 1978 and 1998 (two of the DL harvests were in 1968 and 1988), we recorded a notable increase in the importance of shade-tolerant species (Fig. 5B). By 2008, the SP, ST, and DL treatments averaged about 61% IV of shade-tolerant species. Conversely, the REF and CC treatments were graphically similar to each other in ordination spaces and averaged 38% IV of shade-tolerant species most recently. The two single-tree selection treatments had the greatest importance of hard mast producers (in this case northern red oak and hickory) in 1948 and the greatest reduction in these species through the decades (Fig. 5C). In part, the reduction in hard mast species was due to the intended discrimination against shagbark hickory when selecting trees to harvest up to and including the 1988 harvest cycle. In 1998 and then again 10 years later, the decision was made to preserve all shagbark hickory in the CPL area due to its newly recognized importance as a day roost tree for the federally endangered Indiana bat.

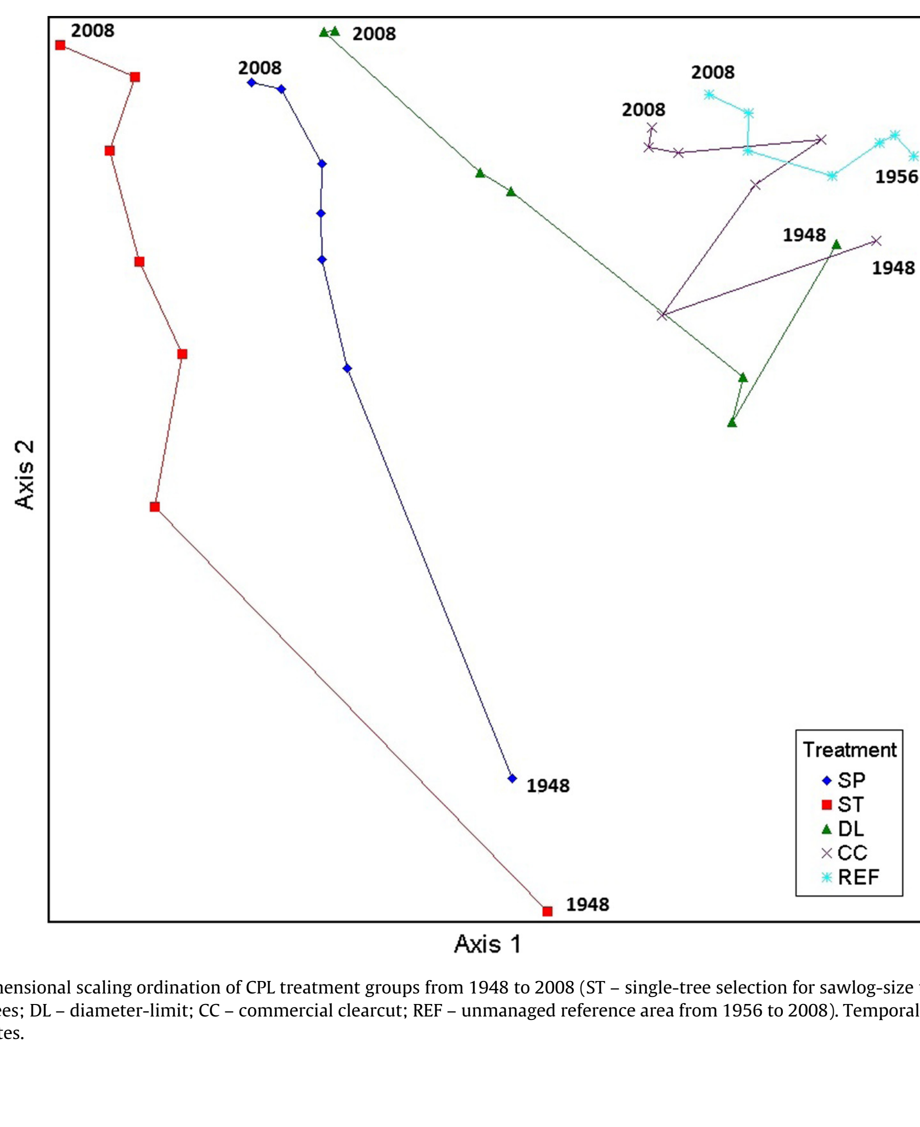

Fig. 4. Nonmetric multidimensional scaling ordination of CPL treatment groups from 1948 to 2008 (ST – single-tree selection for sawlog-size trees; SP – single tree selection for sawlog and pole-size trees; DL – diameter-limit; CC – commercial clearcut; REF – unmanaged reference area from 1956 to 2008). Temporal changes are shown by starting and ending observation dates.

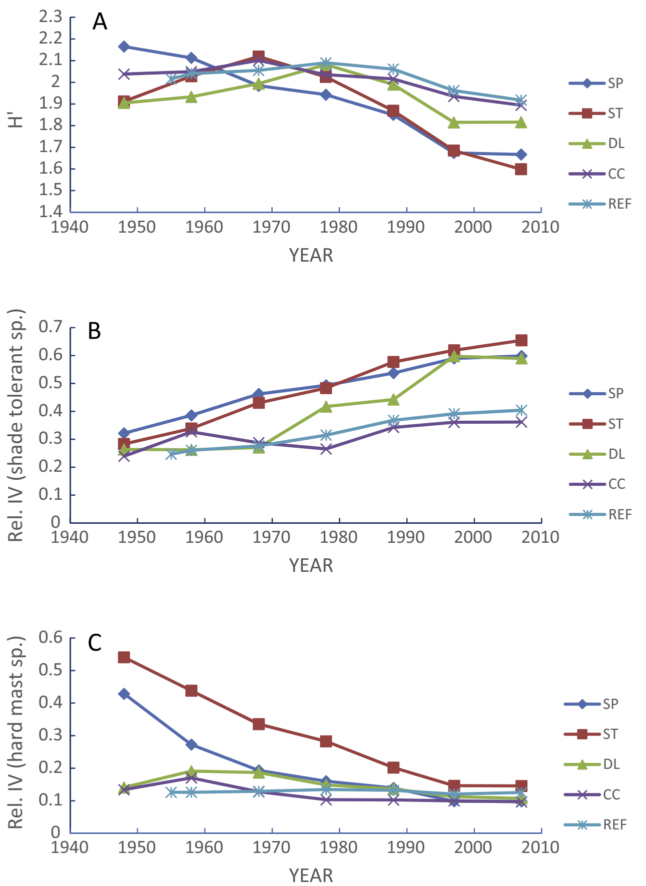

Fig. 5. Diversity (A), relative importance of shade tolerant species (B), and relative importance of hard mast producing species (C) through time by treatment (ST – single-tree selection for sawlog-size trees; SP – single tree selection for sawlog and pole-size trees; DL – diameter-limit; CC – commercial clearcut; REF – unmanaged reference area).

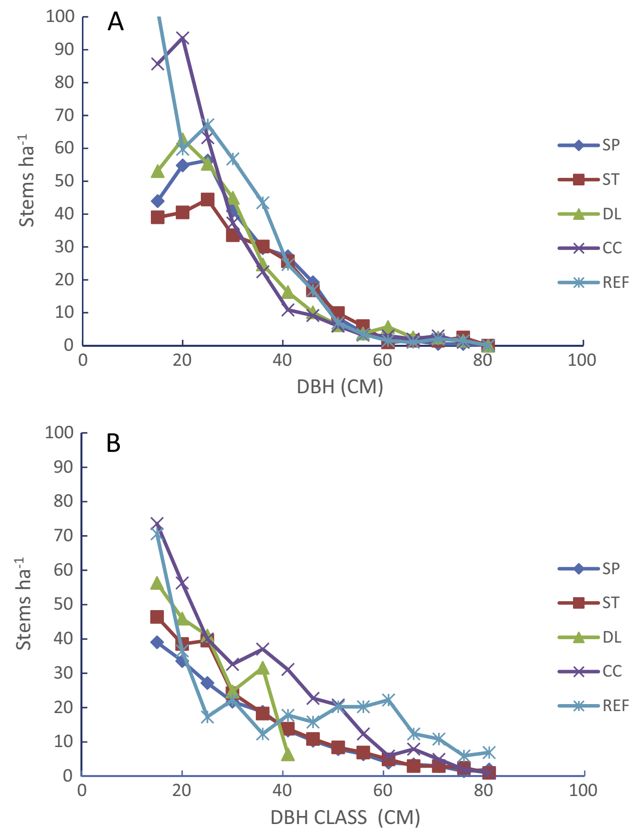

Fig. 6. Size class structure by treatment group in 1948 except REF which is from 1956 (A) and in 2008 (B) (ST – single-tree selection for sawlog-size trees; SP – single tree selection for sawlog and pole-size trees; DL – diameter-limit; CC – commercial clearcut; REF – unmanaged reference area).

3.4. Structure

In 1948 prior to initial treatments, there were weakly expressed unimodal distributions in each of the four areas inventoried (Fig. 6A). Initially, the DL and CC treatments had 20 cm diameter-class modes and the SP and ST treatments had 25 cm diameter class modes. The weakly expressed unimodal distributions in 1948 were correlated with a much larger percentage of shade-intolerant or mid-tolerant species in smaller diameter classes. For example, in 1948 38% of the trees in the ST treatment area were either hickory, oak, black cherry or yellow-poplar in the 15 cm diameter class, none of which are shade-tolerant species. By 2008, only 4% of the trees in the 15 cm dbh class belonged to this group and shade-tolerant species, mostly sugar maple, dominated.

In 2008, the SP and ST treatments both exhibited the reverse-J size class distribution whereas the CC and REF treatments were weakly bimodal (Fig. 6B). The SP and ST treatments were nearly identical for all trees above a sawlog-size DBH threshold and both treatments met the targeted residual stand structure goals described by the BDq parameters. These goals are being met because shade-tolerant species are filling almost all of the recruitment needs in the smaller size-classes. Currently, all of the treatments have 15 cm diameter class modes, an artifact of the lower bounds of the inventory procedures, whereas secondary modes are also identifiable in the CC and REF treatments. The CC treatment has a secondary mode in the 36 cm diameter class and the REF treatment has a secondary mode in the 61 cm diameter class. Shade-intolerant yellow-poplar was largely responsible for the secondary modes in these two treatments. Yellow-poplar exhibited poorly expressed unimodal distributions in 2008 in both treatments (not shown) but the increases of shade-tolerant species in the smaller size classes masked the yellow-poplar cohort from an overall structural perspective.

As expected, the DL treatment has the most truncated diameter class distribution. Nevertheless, after the fourth harvest using the 20 year cutting cycle, there remained about 63 sawlog-size trees ha^{-1} in the DL treatment, which was nearly identical to the density of sawlog-size trees that remained after the first three harvests in 1948, 1968, and 1988. The residual stand structure also included an even greater abundance of pole-sized trees in 2008. Protecting these smaller non-merchantable or pole-sized trees during harvest operations is critical for sustaining the recruitment into larger and merchantable size classes.

3.5. Revenue

After 60 years and 20 separate revenue producing harvests and estimating the residual value of the compartments after the last harvest in 2008, SP had the greatest NPV of $34,000 ha^{-1} using a 4% rate-of-return (Fig. 7). Total NPV of SP exceeded that of DL for the first time in 2008 largely due to the greater value of the residual trees, indicating a potential for greater future returns as well. All three partial harvesting treatments had greater valuations than either CC or REF. Present value of harvests in the SP and ST declined by more than 50% from the 1998 to the 2008 time period. The decline was due to a major a reduction in stumpage values stemming from an economic downturn rather than differences in vol-

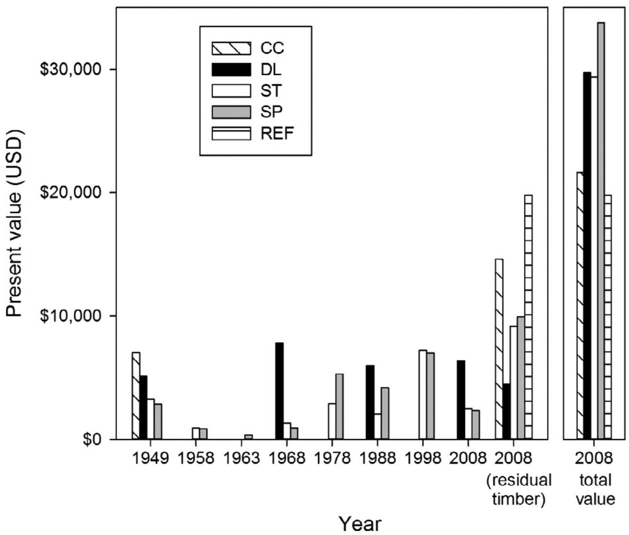

Fig. 7. Present value (USD ha^{-1}) in 2008 of harvest payments by year and treatment using an internal rate of return of 4% (ST – single-tree selection for sawlog-size trees; SP – single tree selection for sawlog and pole-size trees; DL – diameter-limit; CC – commercial clearcut; REF – unmanaged reference area).

ume, grade or species composition, which remained relatively constant as is evident by information presented earlier in this paper. The CC treatment produced the lowest NPV of any of the managed stands and was only valued about \$2000 ha^{-1} more than the REF treatment.

4. Discussion

At the inception of this demonstration, forest researchers in the eastern United States were just beginning to understand the implications of managing individual stands by controlling stocking and species composition (e.g., Hough and Taylor, 1946). The CPL demonstration area was designed to contrast different levels of management and demonstrate a range of outcomes – high-order, good, fair and poor with timber as the primary resource of concern. High-order did result in the greatest NPV with respect to revenue (Fig. 7), but did not produce the most volume and fared poorly relative to the other practices in terms of diversity and retention of hard mast producing species (Fig. 5). As such, as this and similar studies progressed in the 1960s and 1970s, all of the value laden treatment names made when the CPL was established were set aside. Foresters no longer associate uneven-aged management as the highest form of management in the Central Appalachians due to its inability to maintain species composition, nor accept diameter-limit harvesting because it is often exploitive and closer to high-grading than uneven-aged management. And foresters no longer view clearcutting as poor or even destructive because it is understood that many species require disturbances akin to stand replacing events in order to regenerate. Forest researchers here and elsewhere realized that there were advantages to properly applied even-aged management and a policy shift from selective harvesting to even-aged management started in the 1960s on federally managed lands (Roach and Gingrich, 1968). In part, the shift occurred because of the potential to regenerate more diverse forest stands than with partial harvesting. Accordingly, our results did show the commercial clearcut retained more diversity than the other managed stands in 2008, but all of the treatment areas were less diverse in 2008 than in 1948, including the uncut reference stand. Different forms of partial harvesting have had similar effects in New England, the Great Lakes, and the southern Appalachians (Leak, 1996; Neuendorff et al., 2007; Keyser and Loftis, 2013) by periodically harvesting species incapable of regenerating in small gaps (Keyser and Loftis, 2013). This trend has been noted across the region resulting in more homogeneous landscapes and has been referred to as the mesophication of the eastern hardwood forest (Nowacki and Abrams, 2008) whereby more shade tolerant and often less pyrogenic species are steadily gaining in overall importance. Our results clearly reflect this trend and it appears that partial harvesting is accelerating the process (Fig. 4).

It was unexpected that the diameter-limit treatment in this demonstration would outperform the other treatments in terms of wood volume production. Originally described as the "threshold of productive forest practices" (Weitzmann, 1949), today diameter-limit harvesting is not a desirable practice because it is often a surrogate for removing only the valuable timber (i.e., high-grading) and is commonly used on private land (Fajvan et al., 1998; Moss and Heitzman, 2013). Nevertheless, diameter-limit PAI in the CPL's exceeded that of all of treatments after 60 years and four harvests. Smith and Miller (1987) speculated that the diameter-limit treatment in this case study would yield 47 $m^3\ ha^{-1}$ at each 20-year cutting cycle through 2008. Yet in 2008, almost 70 $m^3\ ha^{-1}$ was harvested without any notable deviation from previous post-harvest residual stocking levels. Fast growing yellow-poplar contributed about 35% of the total volume harvested in 2008 and may explain part of the greater than expected productivity, but other potential causal factors are unclear. On the Fernow, similar diameter-limit harvesting regimes also are exhibiting exceptional volume growth (Schuler, 2004), and produced about 30 $m^3\ ha^{-1}\ yr^{-10}$ on sites with a northern red oak site index of 21 (Schuler and McGill, 2007). Moreover, in an ecosystem assessment conducted on the Fernow, above and below ground forest carbon sequestration was 37% greater with diameter-limit and uneven-aged management relative to unharvested forests (Davis et al., 2009). In general, growth rates are influenced by a number of factors, including site quality, age, species composition and stocking (Smith et al., 1997). Stocking is often managed by foresters to optimize growth via thinning in even-aged management and harvest intensity in uneven-aged management. Validation of optimal levels of stocking levels in productive Central Appalachian stands is beyond the scope and data of this case study, but we believe the lower bounds of full stocking leading to high-levels of volume production may not be fully understood (Schuler and McGill, 2007; Davis et al., 2009). This and other long-term silvicultural studies should be used collectively to reexamine stocking recommendations.

In addition to the species diversity issue, the switch to even-aged management in the 1960s gained momentum because it was believed that profits would be greater than those achieved with uneven-aged management (Roach and Gingrich, 1968). But after tracking 20 separate cash transactions over the past 60 years from this effort, the net present value of the revenue generated from the commercial clearcut, including the market value of the standing timber, was less than the NPV for both single-tree selection and the diameter-limit treatments. Only the uncut reference stand, including the market value of the standing timber in 2008, had a lower NPV than the commercial clearcut. We further refined this valuation to include an estimate of cultural treatment costs from field notes recorded over the past 60 years. From 1948 to 2008, CC had one cultural treatment; DL had three; ST had seven; and SP had ten. Assuming a cost of about \$50 ha^{-1} for each entry and using the time since the treatments were conducted based on a 4% rate of return (Miller, 1986), we calculated the present value of these treatments to be about \$109 ha^{-1} for CC, \$350 ha^{-1} for DL, \$1449 ha^{-1} for ST, and \$2440 ha^{-1} for SP. Total valuations including these costs then become \$19,784 ha^{-1} for REF, \$21,522 ha^{-1} for CC, \$27,908 ha^{-1} for ST, \$29,376 ha^{-1} for

DL and \$31,536 ha^{-1} for SP. Rank order remains the same as before cultural treatment costs were estimated but the range of valuations is reduced.

The revenue and cost analyses are partially corroborated by more intensive economic analyses conducted elsewhere. In a northern hardwood stand, NPV was greatest in a "heavy selection cut" (Niese et al., 1995). In Maine, flexible diameter-limit harvesting produced the greatest NPV over other forms of selection harvesting (Kenefic et al., 2005a). Though, Nyland (2005) extended his analysis to 100 years using a growth simulator and found diameter-limit harvesting produced lower present net worth values than selection harvesting. Nevertheless, in many studies, deleterious effects of diameter-limit cutting on tree quality have been observed (e.g., Miller and Smith, 1991; Sendak et al., 2000; Schuler and McGill, 2007; Moss and Heitzman, 2013), which is important because quality and species are the two most important factors in value (Moss and Heitzman, 2013). Continuing the economic comparison among the CPL treatments through 2018 will provide an opportunity to assess the end of rotation value of the commercial clearcut at age 70.

The early objectives of this case study clearly involved the sustained yield of commercial forest products. But in the years since its inception, other forest management concerns have emerged as priorities. For example, running buffalo clover (*Trifolium stoloniferum*) (RBC), a federally endangered plant species, was first discovered in the CPL treatment areas two decades ago and has been carefully tracked in relation to forest operations since (Burkhart et al., 2013). In the 1980s this endemic clover was thought to be extinct, but since its rediscovery, research within the CPL study area and elsewhere on the Fernow has shown that RBC is dependent on periodic and moderate levels of disturbance, such as that resulting from some forms of uneven-aged management (Madarish and Schuler, 2002; Burkhart et al., 2013). The CPL study area also is considered important habitat for the endangered Indiana bat and the threatened northern long-eared bat (*Myotis septentrionalis*). In particular, the remaining shagbark hickories, once considered priority removal species due to low commercial value, are now retained because they serve as critical day roosts for forest dwelling bats, now also battling the catastrophic effects of white-nose syndrome (Thogmartin et al., 2012). The presence of these three federally protected species within the CPL study area is a reminder that habitat management, intentional or not, is a byproduct of forest management and forest managers need to understand the consequences of their decisions on wildlife habitat as well as other ecosystem goods and services.

5. Conclusions

The CPL demonstration on the Fernow Experimental Forest is now in its seventh decade. During this time the focus of federal forest management has evolved from commodity production to a broader range of goods and services. The CPLs were designed to demonstrate a range of forest management practices from best to worst but through time our understanding of each of these practices has changed. Foresters can no longer assign value laden terms to a specific forest management practice because no one practice can deliver all of the goods and services forest managers, land owners and the public want. In this case study, productivity was maximized with diameter-limit harvesting, diversity was best with no management and even-aged management, and quality and value were somewhat better with intensive single-tree selection.

Going forward the data from this and similar work can be used to help calibrate forest growth and yield simulators. Calibrating models with data not used for development is an essential step in the model building process. Data from this work has already been used to evaluate SILVAH, FIBER, NE-TWIGS and OAKSIM simulators (Schuler et al., 1993) and uses for broader scale comparisons continue with other Northern Research Station and university scientists (Adams et al., 2010). The demonstration value of the CPL case study also remains highly relevant in the 21st century. Training and demonstrating a range of forest management options has been a central tenant of the scale and accessibility of the CPL area since its inception. Thousands of people have received guided tours of the CPL demonstration area to learn more about the history and evolving ideas of forest management in the both the Central Appalachians and North America. Looking to the future we are also working to increase the utility of the CPL case study by linking it with similar forest research across the region (Kern et al., 2014). Doing so will increase the scope of inference from site specific silvicultural questions to broader regional forest concerns. Other CPL style demonstrations from the same era exist in Ohio, Pennsylvania, Minnesota, Michigan, Maine and New Hampshire (Kenefic and Schuler, 2008) and the potential insights from a combined meta-analysis are only just beginning. Finally, this and similar long-term replicated studies provide an important benchmark of forest characteristics in the 20th century that will be critical for assessing overall forest health in the 21st century.

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