For. Sci. 64(1):102–111
https://doi.org/10.5849/FS-2016-014

silviculture

Sixty Years of Silviculture in a Northern Conifer Forest in Maine, USA

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In 1950, the US Forest Service initiated a cutting practice level (CPL) study on the Penobscot Experimental Forest in Maine on the basis of findings of a national appraisal of forestland management. Silvicultural treatments, including the selection system with 5- and 15-year cutting cycles, fixed diameter-limit cutting, and variants of commercial clearcutting, were chosen to represent "High-order," "Good," "Fair," and "Poor" cutting practices as then defined for eastern spruce–fir (*Picea–Abies*; northern conifer) forests. After 60 years, selection treatments have maintained a wide distribution of tree sizes, increased the proportion of mature spruce, and decreased the proportion of hardwoods; selection cutting on a 15-year cycle resulted in the highest current stand value. Fixed diameter-limit cutting resulted in the greatest harvest revenue but degraded residual stand composition, structure, and value. Outcomes of commercial clearcutting varied as a function of treatment (none, repeated harvest, or rehabilitation) after the first harvest. After 60 years, the proportion of acceptable growing stock was highest in selection and rehabilitation treatments and lowest in fixed diameter-limit and commercial clearcut treatments. Findings confirm that long-term outcomes of silvicultural treatments with attention to residual stand condition surpass those managed for short-term financial gains with regard to residual stand structure, value, and quality.

Keywords: Penobscot Experimental Forest, cutting practice level study, selection system, diameter-limit cutting, red spruce

In 1946, the US Department of Agriculture Forest Service published a report on the management status of commercial forestland in the United States (Harper and Rettie 1946). This report included qualitative ratings of cutting practices on public and private lands. There were five categories of ratings, called cutting practice levels (CPLs). Practices that met minimum standards for maintaining stocking of commercial species were designated "Fair." The levels above this were "Good" and "High-order," the levels below were "Poor" and "Destructive." Harper and Rettie (1946) concluded that more than half of the nation's managed forestland had been subjected to Poor or Destructive cutting (Table 1).

The first Forest Service experimental forests (EFs) in the northeastern United States were established in the early 1920s (Kenefic et al. 2014). Although most studies on EFs were developed independently to address local management questions (Adams et al. 2003, 2010), the design of some studies was guided by Forest Service Research and Development leadership at national and regional levels. This was true for CPL studies established in the 1940s and 1950s. These studies, consisting of unreplicated treatments applied to 4-ha or smaller experimental units, are still maintained on five EFs in the central hardwood, northern hardwood, and northern conifer forest types (Adams et al. 2012, Kenefic and Schuler 2008).

We focused on 60-year results of the CPL study on the Penobscot EF in Maine. This is the oldest study at that location, predating the larger, more intensively studied compartment management study (Brissette and Kenefic 2014, Sendak et al. 2003). Although the CPL study is not replicated, length of observation, consistency in treatment application and data collection, and similarity to studies at other sites (e.g., Schuler et al. 2016) make this a unique opportunity for long-term evaluation of silvicultural outcomes. However, there have been no publications since Hart (1964) reported 9-year results.

Our objectives were to quantify long-term (60-year) treatment effects on tree species composition, stand structure, volume growth, quality, and value and to compare those findings to initial CPL categorizations, early results (Hart 1964), and outcomes from studies on other EFs (i.e., Bartlett EF in New Hampshire and Fernow EF in West Virginia). We hypothesized that treatments designated High-order and Good would result in a greater range of tree sizes,

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Manuscript received July 22, 2016; accepted July 27, 2017; published online August 31, 2017.

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Acknowledgments: *Funding for this project was provided by the US Forest Service, Northern Research Station and the US Forest Service, Research and Development, National Research Data Archive. Justin Waskiewicz of the University of Vermont assisted with data preparation and summary and reviewed an earlier version of the manuscript. Additional reviews were provided by Robert M. Frank Jr. (US Forest Service, retired) and Anthony D'Amato (University of Vermont). We also thank the two anonymous reviewers for their thoughtful feedback and suggestions.*

Table 1. CPL definitions and estimated percentage of managed forestland in each level, as reported by Harper and Rettie (1946) and McLintock (1950).

CPL	Definition	Percentage of managed US forest land, 1946
High-order	Intensive silviculture, including investment in cultural practices such as planting, timber stand improvement, and thinning, to maintain the quality and quantity of yields. Land is managed to full productive capacity, considering desired species composition and structures.	3
Good	Harvesting is in accordance with good silvicultural practice and leaves a residual stand composed of vigorous trees of desired species. Substantially better than Fair order, with some elements of High-order.	20
Fair	The minimum cutting practice that will maintain a reasonably productive forest with desired species and stocking.	25
Poor	Leaves scattered, poor quality and unmerchantable trees with limited means for natural regeneration of desired species. Deteriorates the quality of the residual stand over time.	46
Destructive	Creates a residual stand without timber or means for natural regeneration.	6

higher proportions of desired species and quality trees, and greater growth and value than treatments representing Fair or Poor practices.

Methods

Study Area

The CPL study was established in 1950 on the Penobscot EF in the towns of Bradley and Eddington, Maine (44°52′ N, 68°38′ W). The Penobscot EF is in the Acadian Forest (Halliday 1937, Braun 1950) and comprises northern conifers mixed with hardwoods (i.e., mixedwoods). Species groups defined for this analysis include spruce (red spruce, *Picea rubens* Sarg.; white spruce, *Picea glauca* (Moench) Voss; and black spruce, *Picea mariana* (Mill.)), eastern hemlock (*Tsuga canadensis* (L.) Carrière), balsam fir (*Abies balsamea* (L.) Mill.), northern white cedar (*Thuja occidentalis* L.), other softwoods (primarily *Pinus strobus* L.), and hardwoods. Hardwoods are predominantly red maple (*Acer rubrum* L.) and paper birch (*Betula papyrifera* Marshall) but include other maple and birch species, aspen (*Populus spp.* L.), and American beech (*Fagus grandifolia* Ehrh.). Before the Forest Service study, the forest had been repeatedly harvested and consisted of aggrading second growth with varying densities of residual older trees (Kenefic and Brissette 2014). In 1950, tree species composition in the study area was 79% softwood and 21% hardwood.

Study design included four of the five CPLs defined in the national appraisal (Harper and Rettie 1946): 5-year single-tree selection (SC05, High-order), 15-year single-tree selection (SC15, Good), 15-year fixed diameter-limit cutting (FDL, Fair), and commercial clearcutting (CC, Poor; McLintock 1950). Treatments were defined based on earlier work by the Forest Service suggesting that uneven-aged silviculture (i.e., single-tree selection cutting) was appropriate in eastern spruce–fir forests because of the preponderance of shade-tolerant species and the multiaged condition of the forest (Westveld 1938).

The CPL study was installed in a 16-ha area divided into four 4-ha experimental units called management units. The management unit to which commercial clearcutting was applied was later subdivided to test treatment alternatives. Soils in the study area are in the Monarda (loamy, mixed, active, acid, frigid, and shallow Aeric Endoaquepts) and Burnham (loamy, mixed, superactive, nonacid, frigid, shallow Histic Humaquepts) soil series (US Department of Agriculture, 2014, 2016). These soils are formed from dense glacial till and are generally poorly to very poorly drained. Topography is flat with slope less than 15%.

Silvicultural Treatments

Single-tree selection cutting has been applied in the CPL study on 5- and 15-year cutting cycles, with 12 and 5 treatments in SC05 (management unit 90) and SC15 (management unit 91), respectively, since 1950. The selection system is used to create and maintain uneven-aged stands by harvesting mature trees, tending immature classes, and establishing regeneration at each entry. Overall, treatments were intended to decrease the amount of cull, balsam fir (because of short pathological longevity and susceptibility to spruce budworm, *Choristoneura fumiferana*), and hemlock and to increase spruce—a historically more prevalent (Seymour and Hunter 1992) and commercially valuable shade-tolerant conifer in the region. Residual stand structure in the Penobscot EF selection treatments is defined using the BD*q* method (Guldin 1991, Marquis 1978), in which target residual basal area, maximum diameter (maxD), and *q*-factor (ratio of numbers of trees in consecutive 5-cm dbh classes) are used to prioritize removals in

Management and Policy Implications

The work reported here demonstrates the value of long-term studies for understanding the implications of alternative forest management scenarios. CPL studies on the Penobscot EF and elsewhere provide an opportunity to assess outcomes over a period longer than one scientist's career and to validate local work through cross-site comparison of like experiments. Our objective was to examine impacts of a range of silvicultural treatments on northern conifer forest structure, composition, productivity, and quality. Findings suggest that selection cutting maintained a broad range of diameter classes, increased composition of desired species, and retained quality and financially valuable trees. Residual conditions associated with 5- and 15-year cutting cycles were not sufficiently different to warrant different qualitative descriptors (i.e., High-order and Good; Harper and Rettie 1946, McLintock 1950). In addition, although FDL and repeated commercial clearcutting are less desirable than selection cutting with regards to changes in composition, structure, residual tree quality, and residual stand value, the number of harvests influenced results such that CC was in many ways better stocked with desired species and trees than FDL in year 60. In contrast, the CC+R treatment improved species composition and quality, thus meeting the characteristics of a High-order treatment as originally defined, albeit at the expense of converting the initially structurally diverse stand to a more uniform, single-cohort structure. These outcomes support the need for stand tending, retention of quality trees of desired species, and attention to regeneration establishment and release in managed northern conifer stands.

conjunction with marking guides on the basis of tree quality and species (Seymour and Kenefic 1998, Brissette and Kenefic 2014; Table S1).

Fixed diameter-limit cutting as applied on the Penobscot EF is a form of exploitative cutting (high grading) in which merchantable trees above species-specific size thresholds are removed without tending; nonmerchantable trees are left as residuals (Kenefic et al. 2005). The harvest return interval in the FDL (management unit 92) is 15 years, with five harvests since 1950. Species- or species-group size thresholds for removal over the period of the study have been (±5 cm dbh) 14 cm for fir and hardwoods (excluding paper birch), 19 cm for white cedar and paper birch, 24 cm for spruce and hemlock, and 27 cm for white pine.

Commercial clearcutting, also called unregulated harvesting or logger's choice, is an exploitative treatment in which all merchantable trees are removed (Kenefic et al. 2014). Unlike silvicultural clearcutting, objectives are to maximize volume and value removal, not to establish regeneration. The size threshold for removal in the study varied from 13 to 15 cm dbh, although larger trees were left if the logger chose not to take them. At the time of our analysis, this treatment had been applied once in CC (management unit 93A), twice in CC2 (management unit 93B), and once with later overstory removal (liberation cutting) and precommercial thinning to a 2.4- by 2.4-m spacing, favoring spruce, as a rehabilitation treatment (management unit 93C, CC+R).

Data Collection and Summary

From 1950 until 2000, 100% inventories of trees 11.4 cm dbh or larger were made every 5 years and before and after cutting; species, dbh class (nearest 2.5 cm), and merchantability status (merchantable or cull: <50% merchantable by volume) were recorded. Saplings (1.3–11.3 cm dbh) were tallied in 2- by 200-m transects, 100 m apart (2% sample of management unit area). Beginning in 2000, inventories of trees 1.3 cm or larger were made approximately every 10 years and before and after cutting on nested, circular permanent sample plots on a systematic grid (Waskiewicz et al. 2015). Overstory trees (≥11.4 cm dbh) were measured to the nearest 2.5 cm on 0.08-ha plots (12% sample of management unit area); saplings were measured on 0.02-ha plots (5% sample of management unit area). Mortality and ingrowth were recorded. The most recent inventory data available at the time of this assessment were from 2010 (commercial clearcut management units) and 2011 (selection and FDL management units); these are considered representative of year 60 for discussion and annualized as needed for comparison. Because of inconsistencies in cull classification over time associated with changing merchantability standards, tree quality assessments were made in 2014 for the purpose of this analysis. Overstory trees on each permanent sample plot were categorized as acceptable growing stock or unacceptable growing stock (tree without a merchantable 2.4-m log or with poor form or risk factors, suggesting it will die or decrease in volume, vigor, or quality before the next harvest (Nyland 1996).

Calculations

Species composition by basal area of trees 1.3 cm dbh (percent) and larger and number of trees per hectare (tph) were calculated for each management unit in years 0 (1950) and 60 (2010 or 2011, depending on data availability). Product sizes were defined as poles (11.4–21.3 cm dbh), small sawtimber (21.4–31.5 cm dbh), and medium to large sawtimber (≥31.6 cm dbh). Volume (m^3/ha) and change in volume over time were calculated using a local volume table (see Sendak et al. 2003) and used to determine annualized gross growth, net growth, mortality, and harvest. Harvest volumes were defined as differences between pre- and postharvest inventories excluding mortality. Percentages of acceptable and unacceptable growing stock by basal area of trees 11.4 cm dbh or larger were calculated by treatment. For selection treatments, distribution of tph by dbh class was compared to structural goals (McLintock 1950, Waskiewicz and Kenefic 2012).

Financial Value

Actual harvest volume and cost data were not available for past harvests. To compare value over time, the Northeastern variant of the Forest Vegetation Simulator was used to calculate standing volumes of pulpwood in cubic feet (ft^3) and sawlogs in thousand board feet (mbf) for the initial treatment areas in 1950 and current treatment areas (2010 or 2011) for live trees 11.3 cm dbh or larger as well as all harvested pulpwood and sawlog volumes. Volumes were converted to cords assuming two cords per mbf, 87 ft^3/cord for spruce and fir, 84 ft^3/cord for other softwoods, and 80 ft^3/cord for hardwoods. An annual market price series (1950 to 2011) was compiled from actual species- and product-class-specific stumpage prices reported by the University of New Hampshire Extension Service (1950–58) and the Maine Forest Service (1959–2011). Reported prices (nominal) were adjusted by the Producer Price Index (all commodities) to eliminate influence of inflation. Volumes were multiplied by the compiled real prices to determine the initial (year 1950) and current value for each treatment (in year 2010 or 2011) as well as the sum total of all harvest revenue and the cumulative value (sum of harvest revenue and current stand value) for each treatment. All values are reported in 2011 dollars (real values), allowing for a comparison of relative financial performance by treatment. Cumulative values were discounted using a discount rate of 2% to a common point of reference, 1950. Lastly, values were converted from dollars per acre to dollars per hectare.

Analysis

Because of the lack of replication, we did not test for statistically significant differences in treatment means. Instead, inferences were drawn from population values (100% inventories) before 2000 and from permanent sample plot means and standard deviations after 2000. Interpretations are strengthened through comparison to outcomes from other studies.

Results

Treatment Effects

Single-Tree Selection: 5-Year Cutting Cycle

The 1950 range of diameter classes in SC05 was maintained through 2011, but the distribution of trees across product size classes changed (Figure 1A). Since 1950, density of poletimber decreased by 73% and was 54% of the residual goal in 2011; sawtimber density increased and exceeds the goal.

Spruce increased over the study period as a percentage of basal area; hardwoods and white cedar decreased, and other species were unchanged (Figure 2A). The increase in spruce can be attributed to an increase in spruce sawtimber basal area (Table 2). The percentage of spruce in poles decreased between 1950 and 2011, with no change evident in spruce saplings; fir increased in both classes. Overall, hemlock remained the most abundant species in terms of basal area (Figure 2A).

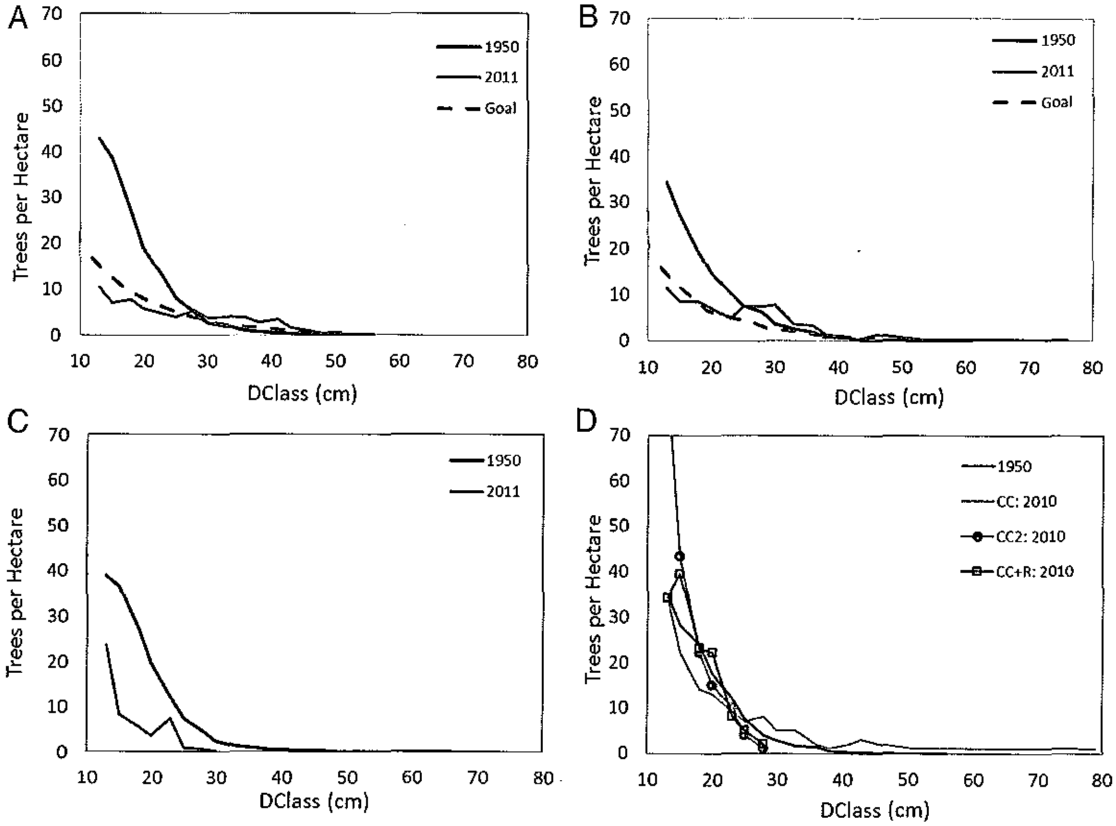

Figure 1. Diameter distributions represented by tph in year 0 (1950) and year 60 (2010 or 2011) for each treatment; selection treatments include current structural goals: (A) SC05, (B) SC15, (C) FDL, and (D) CC.

Change in volume over time shows the sawtooth pattern typical of repeated selection cuts (Figure 3). Volume in 2011 was similar to that in 1950, with harvest approximating growth. Mortality was low relative to the FDL and commercial clearcuts (Table 3).

Single-Tree Selection: 15-Year Cutting Cycle

After five entries, the range of diameters in SC15 was wider than in the pretreatment stand (Figure 1B). However, poletimber density decreased by 57% whereas sawtimber densities increased by 30% and 90% in the small and medium to large classes, respectively. Small sawtimber density exceeded the structural goal by 45% in 2011.

Spruce and hemlock increased over the study period as a percentage of basal area; fir, hardwoods, and white cedar decreased, and other species were unchanged (Figure 2B). Increases in spruce were due to basal area growth of merchantable-sized trees rather than ingrowth (Table 2). More than 80% of spruce was in the sawtimber classes in 2011.

Standing volume in 2011 was similar to that of the pretreatment stand (Figure 3 and Table 3). Mortality was similar to that observed in the other selection treatment and harvested volume approximated growth.

Fixed Diameter-Limit Cutting

Stem density and range of size classes was reduced over the study period in FDL (Figure 1C). All trees in the medium to large sawtimber classes were removed, decreasing observed maxD from greater than 60 cm (1950) to less than 30 cm dbh (2011). Densities of trees in the pole and small sawtimber classes were reduced by 65% and 87%, respectively.

Fir composition as a percentage of basal area increased 3-fold over the study period, largely because of ingrowth into the sapling classes (Figure 2C and Table 2). More than 80% of fir basal area was less than 11.4 cm dbh in 2011. Spruce and hemlock compositions varied among permanent sample plots, with no clear management unit-level directional changes over time.

Repeated diameter-limit cutting considerably lowered standing volume between 1950 and 2011 (Figure 3 and Table 3). Mortality was greater than that in selection treatments, and harvested volume exceeded net growth.

Commercial Clearcut

Density and relative size-class distribution of trees after 60 years varied depending on actions after the initial (1950) harvest (Figure 1D). Among commercial clearcut treatments, the single entry resulted in the largest range in diameters in 2010. Size class distribution shifted toward sawtimber, with 59% and more than 300% increases in small and medium to large sawtimber density, respectively. Poletimber density decreased by 19%. After the second commercial clearcut in CC2, the range in diameters was truncated. Poletimber density increased by 40% relative to 1950 whereas small and medium to large sawtimber densities decreased by 62% and 33%, respectively. In CC+R, the maxD of the residual stand was lowered, poletimber density increased by 7%, small sawtimber decreased by 57%, and all medium to large sawtimber size trees were removed.

Differences in species composition between 1950 and 2010 varied as a function of treatment after the initial harvest. Percentage of spruce decreased in commercial clearcuts without rehabilitation, but it was comparable to the original stand in CC+R (Figure 2D). An

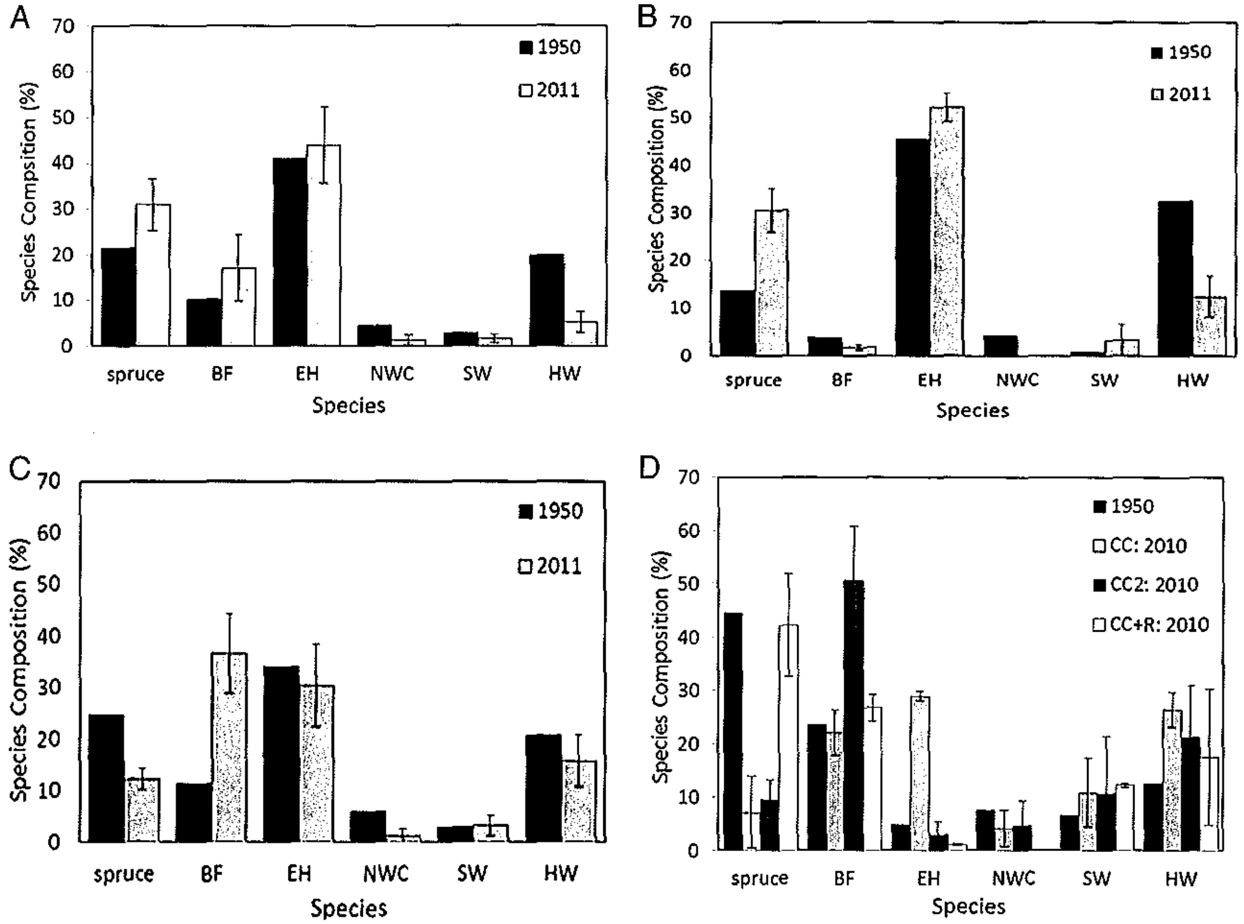

Figure 2. Species composition in year 0 (1950) and year 60 (2010 or 2011) by treatment where spruce is spruce species, BF is balsam fir, EH is eastern hemlock, NWC is northern white cedar, SW is other softwood species, and HW is hardwood species: (A) SC05, (B) SC15, (C) FDL, and (D) CC. Error bars are ±1 *SD*.

increase in fir was also observed in CC2. Percentages of hemlock and hardwoods increased between 1950 and 2010 in the single-entry commercial clearcut treatment but were similar to pretreatment levels in the commercial clearcuts with multiple entries. Relative abundance of other species did not change.

Harvest was less than growth in the single-entry commercial clearcut. Alternatively, in the commercial clearcuttings with repeated entries harvests exceeded growth (Table 3).

Quality and Value

In 2014, acceptable growing stock (as a percentage of basal area ≥11.4 cm dbh) was highest in selection treatments and CC+R (Figure 4). The lowest ratio of acceptable to unacceptable growing stock was observed in FDL and CC. Treatment differences in residual stand quality were reflected in financial value. Real harvest revenue ranged from $1,440 (CC) to $5,611 (FDL), with the highest cumulative value (harvest revenue plus current stand value) in the selection stands and lowest value in the CC+R. Discounted cumulative value was highest in the FDL, followed by selection treatments, and lowest in the CC (Table 4).

Discussion

After 6 decades, the Penobscot EF CPL study provides a unique opportunity to review long-term outcomes of forest management in northern conifers. Hart (1964) observed early divergence among cutting practices, including changes in species composition and differences in growth rates among treatments. Over the first 9 years of the study, he reported that the proportion of hardwoods increased in CC, but it either decreased or remained unchanged in selection and FDL treatments. Net volume growth in CC was about half that in other management units. Likewise, volume growth was lower in CC than other treatments after 7 years in the Bartlett EF CPL study (Blum and Filip 1963). Fifty years later, we observed even greater disparities between treatments on the Penobscot EF.

Structure and Quality

After 60 years, the range of tree sizes in SC05 and SC15 CPL treatments was greater than in FDL or commercial clearcutting with repeated harvests, CC2. However, relative to diameter distribution goals, selection treatments had poletimber deficits and sawtimber excesses. Seymour and Kenefic (1998) observed similar lack of balance in other single-tree selection stands at the Penobscot EF and suggested that poletimber deficits resulted from greater emphasis on retention of vigorous sawtimber than adherence to structural goals. In Appalachian hardwoods, Lamson and Smith (1991) reported excess sawtimber relative to structural goals after 30 years of single-tree selection cutting on the Fernow EF.

On the Penobscot EF, excess sawtimber in the selection treatments may be the result of large, overstory spruce retained as seed sources (personal observation). These trees, many of which would

Table 2. Product class distribution of spruce, fir, and hemlock by treatment, as percentage of basal area in year 0 (1950) and year 60 (2010 or 2011).

Treatment	Species	Year	Saplings	Poletimber	Sawtimber
SC05	Fir	1950	19.0	64.5	16.5
		2011	77.9 (11.5)	21.5 (11.5)	0.6 (1.4)
	Hemlock	1950	6.1	41.7	52.2
		2011	24.0 (27.4)	11.1 (3.3)	64.9 (30.5)
	Spruce	1950	3.9	46.9	49.2
		2011	9.7 (9.8)	4.0 (6.1)	86.2 (13.7)
SC15	Fir	1950	50.8	46.6	2.5
		2011	66.6 (51.6)	33.3 (51.6)	0.0 (0.0)
	Hemlock	1950	6.8	27.7	65.4
		2011	14.4 (12.0)	19.1 (6.1)	66.4 (13.2)
	Spruce	1950	9.2	52.2	38.6
		2011	3.5 (5.8)	14.2 (10.1)	82.2 (14.8)
FDL	Fir	1950	19.4	64.6	15.9
		2011	81.0 (16.4)	18.9 (16.4)	0.0 (0.0)
	Hemlock	1950	10.0	41.6	48.4
		2011	35.1 (26.4)	41.1 (18.4)	23.9 (25.3)
	Spruce	1950	5.3	53.4	41.2
		2011	16.9 (15.7)	46.8 (35.3)	36.2 (32.5)
CC	Fir	1950	13.3	55.9	30.8
CC		2010	36.7 (10.3)	59.6 (15.3)	3.6 (5.5)
CC2		2010	41.1 (10.3)	51.9 (20.0)	6.9 (9.7)
CC+R		2010	39.1 (47.6)	43.5 (30.9)	17.3 (16.7)
CC	Hemlock	1950	3.3	47.4	49.3
CC		2010	0.0 (0.0)	2.3 (0.5)	97.6 (0.5)
CC2		2010	0.0 (0.0)	50.0 (70.7)	50.0 (70.7)
CC+R		2010	100 (0.0)	0.0 (0.0)	0.0 (0.0)
CC	Spruce	1950	2.9	46.5	50.6
CC		2010	7.1 (10.2)	56.1 (62.0)	36.6 (51.8)
CC2		2010	23.3 (4.1)	43.7 (2.3)	33.0 (1.8)
CC+R		2010	32.7 (17.1)	53.3 (5.9)	14.0 (11.2)

Note: Standard deviation shown in parentheses.

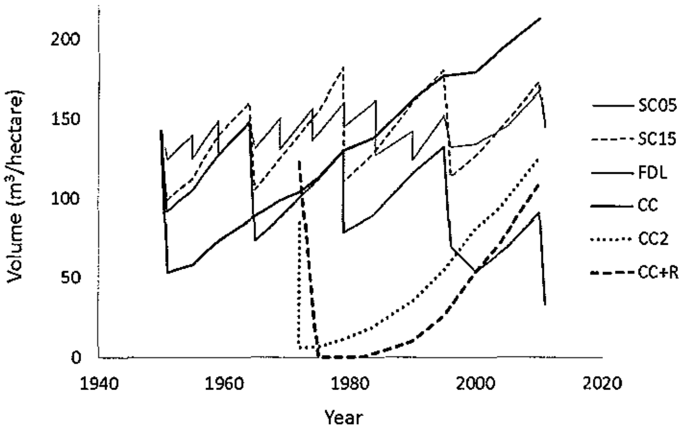

Figure 3. Changes in merchantable volume (m^3/ha) over time by treatment.

Table 3. Standing merchantable volume (m^3/ha) in year 0 (1950) and year 60 (2010 or 2011) as well as volume growth, mortality, and harvest (m^3/ha/year), by treatment.

Treatment	Volume year 0 (m^3/ha)	Volume year 60	Gross growth (m^3/ha/yr)	Net growth	Mortality	Harvest
SC05	142.78	145.55 (40.39)	4.36	3.74	0.62	3.69
SC15	127.80	141.57 (58.39)	5.07	4.47	0.60	4.24
FDL	139.60	33.09 (15.48)	4.20	3.39	0.81	5.17
CC	142.19	213.08 (15.33)	3.58	2.66	0.92	1.48
CC2	–	125.04 (8.85)	3.77	2.73	1.04	3.01
CC+R	–	108.36 (50.78)	3.60	2.96	0.64	3.52

Note: Standard deviation shown in parentheses.

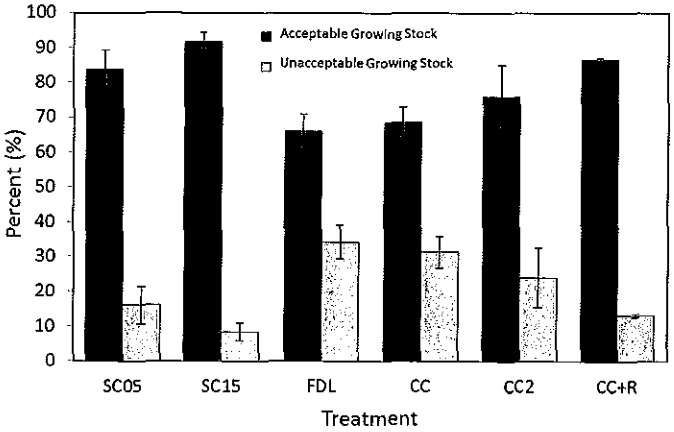

Figure 4. Acceptable and unacceptable growing stock as a percentage of basal area in trees ≥11.4 cm dbh by treatment, 2014. Error bars are ±1 *SD*.

Table 4. Real value and harvest revenue by treatment expressed in constant dollars (2011 = 100).

Treatment	Stand value year 0 ($/ha)	Stand value year 60	Harvest revenue	Cumulative value (harvest + year 60)	Discounted cumulative value
SC05	3,745	1,159	5,488	6,647	3,766
SC15	2,491	1,600	5,000	6,600	3,432
FDL	4,371	160	5,611	5,770	4,234
CC	3,764	1,296	1,440	2,736	1,828
CC2	–	259	3,286	3,544	2,711
CC+R	–	178	2,414	2,592	2,123

otherwise be cut per structure or quality goals defined in the study plan, increase the proportion of high-risk sawtimber in the residual stand. From a commodity perspective, high-risk trees (in this case, prone to stem breakage because of past logging damage and subsequent decay) increase the proportion of unacceptable growing stock.

Ranges of diameter classes were truncated relative to pretreatment conditions in FDL and CC2. These results are comparable to those from other studies at the Penobscot EF, where almost all merchantable medium to large sawtimber trees were removed through repeated fixed diameter-limit and commercial clearcutting (Kenefic et al. 2005, 2014). Schuler et al. (2016) found similar results after 60 years of diameter-limit cutting in the Fernow EF CPL study. Simulations by Bohn et al. (2011) in northern hardwoods suggest that although the amount of residual sawtimber after repeated diameter-limit cutting is a function of initial stand condition and harvest intensity, sawtimber yield generally decreases over time. Decreases in tree quality have also been reported in some other studies of diameter-limit cutting, including the Fernow EF CPL (Schuler et al. 2016). Similarly, Eyre and Zillgitt (1953) observed a drop in the percentage of grade 1 sawlogs after heavy cutting in northern hardwoods. In this study, the highest ratio of unacceptable to acceptable growing stock in 2014 was in the heavy removal treatments (i.e., FDL and commercial clearcuttings without rehabilitation). In the CC treatment, 60 years of regrowth mitigated removals of large trees with regard to the range of dbh classes present.

The CC+R treatment represents silvicultural rehabilitation, intended to improve composition, quality, and value of a degraded stand (Kenefic 2014). Although the range of tree sizes narrowed, the proportion of unacceptable growing stock was low relative to the other commercial clearcut treatments, and percentage of spruce increased. Research in northern hardwoods and mixedwoods has shown positive impacts from rehabilitation in cutover stands. Bedard et al. (2014) reported increases in acceptable growing stock after rehabilitation in northern hardwoods; Kenefic et al. (2014) observed an increase in residual stand quality after precommercial crop tree release in degraded mixedwood stands.

Composition

The forestland that became the Penobscot EF, similar to most Maine forests, was selectively harvested repeatedly before 1950 (Safford et al. 1969). Across the spruce–fir region, partial cutting in the 1800s and early 1900s removed valuable softwoods for sawlogs and pulpwood and changed species composition (Westveld 1928, 1930). This likely increased abundance of hardwoods at the location of the CPL study, where generally impeded soil drainage suggests a site characteristic of Westveld's (1953) spruce-fir "flats."

In the northern United States, repeated single-tree selection cutting has been shown to favor shade-tolerant species and reduce species diversity over time (Eyre and Zillgitt 1953, Kern et al. 2014, Leak et al. 2014). In SC05, spruce basal area increased due to growth of overstory trees rather than recruitment of new growing stock; saplings and poletimber were composed mainly of fir after 60 years. The more competitive nature of fir regeneration relative to spruce may be a factor in composition of the new cohorts (Hart 1963, Moores et al. 2007). Although not quantified in the present study, gap size may also be a contributing factor in establishment and growth of spruce. Dumais and Prèvost (2014) found spruce were outcompeted by fir in small- (<100 m^2) and large- (700 m^2) but not intermediate-sized (100–300 m^2) gaps. In the SC15, spruce composition increased across all product size classes; this may be a result of gap sizes more favorable to spruce establishment and growth in this treatment, which had a lower residual basal area than SC05.

In treatments with heavier removals, spruce composition was reduced unless steps were taken to tend the residual stand. Repeated removal of large, high-quality trees in FDL left a degraded stand with a higher composition of fir and no reduction in hardwoods. Archambault et al. (2006) observed that stand composition after repeated diameter-limit cutting varied depending on microsite conditions and composition of advance regeneration. In addition, residual diameter-limit cut stands are often composed of clumps and voids of trees (Bohn 2005), creating light conditions in openings that may be more suited to fir (Seymour et al. 2006).

Harvesting that removes all merchantable material, such as those in the CC and CC2 treatments, emphasize short-term financial return rather than residual stand tending. On the Penobscot EF, spruce species declined, likely because of competition from more aggressive fir and hardwood species, fewer seed sources, and unfavorable regeneration microsites associated with hardwood litter (Weaver et al. 2009, Weiss and Millers 1988). In CC and CC2, hardwood composition in year 60 resulted in classification of the residual stands as mixedwood ($<75\%$ softwood; Kabrick et al. 2017) rather than softwood.

All treatments, with the exception of CC and CC2, reduced or eliminated white cedar. This is due to marking guidelines that prioritized removal of trees with internal decay (common in white cedar) in selection and CC+R treatments as well as the diameter limit for white cedar (19 cm dbh) in FDL. In addition, heavy browsing by white-tailed deer (*Odocoileus virginianus*) has been observed on white cedar in partially cut stands elsewhere on the Penobscot EF and causes recruitment failures (Larouche et al. 2010). In light of concerns about white cedar sustainability on the Penobscot EF (Larouche et al. 2010) and elsewhere in the region (Boulfroy et al. 2012), retention of white cedar for seed and biodiversity has been prioritized in selection treatments since 2008. It is too soon to tell if this will affect stand composition.

Growth

Annualized gross and net growth rates were highest in selection treatments. Relative to 10-year growth rates observed by Hart (1963), long-term net growth decreased in SC05 and SC15 by 1.7 and 1.0 m^3/ha/yr, respectively. However, annual net growth rates observed over 60 years are similar to those recorded by Frank and Bjorkbom (1973) in softwood selection stands elsewhere on the Penobscot EF. Net growth in the present study was lowest in more exploitative FDL and commercial clearcutting treatments. Other studies in both hardwood- and softwood-dominated forests in the Northeast support these findings. Sokol et al. (2004) observed that residual spruce in diameter-limit cut stands grew more slowly than those in selection stands over a 40-year period. Similarly, Nyland (2005) predicted annual production in northern hardwood selection stands to be greater than in diameter-limit cut stands, whereas Ward et al. (2005) observed lower growth in exploitatively cut oak (*Quercus*) stands than those where silvicultural treatments were applied. These findings differ from those at the Fernow EF, where diameter-limit cutting resulted in higher production than selection cutting over 60 years (Schuler et al. 2016). A higher diameter-limit threshold (39 cm dbh), difference in site quality, and increased abundance of fast-growing shade-intolerant species (yellow-poplar, *Liriodendron tulipifera* L.) in that study, may explain this difference.

Financial Return

The primary focus of the Penobscot EF CPL was long-term, stand-level outcomes accruing from different forest practices, not the potential financial returns from each. However, there is interest in the relative performance of each treatment with respect to a single value criterion such as that commonly considered by forest managers. By calculating the net present value, differences between treatments in product class, species values, and timings of harvests are incorporated.

The ability to calculate a standard net present value for each treatment was limited by the lack of tree grade, cost, and revenue information for each treatment. Instead, we compared the relative financial performance of each treatment using the cumulative value (real 2011 dollars) and discounted cumulative value (based on the 2% discount rate).

Treatments varied widely in the types of products removed over the 60-year study period as well as in final stocking. Harvest revenues and inventory values over the study period are a function of both total volume and distribution of trees among product classes. However, tree grade data were not available. As a result, value of sawtimber in treatments with higher proportions of unacceptable growing stock (i.e., commercial clearcuttings without rehabilitation and FDL) might be inflated. In addition, revenues are influenced by changes in relative values of species and products over time. For example, real prices of spruce and fir pulpwood were similar in 1950 and 2010 whereas hardwood pulpwood prices increased. As a result, hardwood species that were historically discriminated against in the selection treatments because of low value were worth more than preferred softwoods in 2010 (Table S2). Likewise, prices for white pine sawtimber almost doubled over the study period, causing pine trees left after the 1950 commercial clearcut (likely poor quality) to inflate present stand value in that treatment.

A forest manager seeking to maximize value over the life of the stand must incorporate both returns from intermediate harvests and final stand value because residual stand condition defines future management options. Although harvest value was highest in FDL, value of the standing volume in 2011 was lowest in this treatment (Table 4), due largely to the repeated removal of high-quality trees without tending of the residual stand. In addition, because harvest volumes exceed growth in this treatment, the high harvest revenue is not anticipated to continue into the future (Table 3). Commercial clearcutting treatments resulted in the lowest harvest values and, with repeated entries, the lowest current stand values. Selection cuttings had the highest cumulative harvest and current stand values, similar to findings from the Fernow EF CPL study (Schuler et al. 2016). Comparing the stream of incomes and final stand values from the perspective of the starting point for the Penobscot EF, the discounted cumulative revenues range from $4,234/ha under the FDL treatment to $1,828/ha for CC. However, it is important to note that the stands were not identical at the time of initial treatment; the stand to which FDL was applied had the highest initial value.

These results are validated by the widespread use of diameter-limit cutting in commercial forests in Maine and elsewhere in the United States (Fajvan et al. 1998) and Canada (Schwan and Elliott 2010). When considering a stand, intermittent removals of high-value trees do return the highest financial value in discounted terms—even including the final standing volume. However, it is important to note that this is equivalent to a one-rotation view of the forest. Over the long term. harvesting more than growth drives down residual stand stocking and value. In addition, repeated removal of the highest-value trees limits options for management by degrading residual composition, structure, volume, and quality. Current stand condition will have a greater impact on financial return in coming years; a subsequent longer-term analysis of results may reflect that.

CPLs

Considering the initial goals of this study and definitions presented in Harper and Rettie (1946), our findings suggest that the qualitative rankings are generally appropriate, at least with the regard to selection versus fixed diameter-limit and commercial clearcutting. However, the 60-year results do not support the conclusion that the selection treatment with more frequent entries is a better practice than selection with a longer cutting cycle with regards to species composition, quality, and growth. In fact, value of current inventory is higher in SC15 than SC05. In theory, less-frequent entries confer less control over species composition and decrease potential to capture mortality. However, lower allowable cut in SC05 (in fact, harvest levels may not be sufficient to support commercial operations in many regions) may result in reduced capacity to release desired lower-stratum trees such as spruce.

Likewise, classification of commercial clearcutting without rehabilitation as Poor, and FDL as Fair, is not as clear as suggested in the CPL definitions. Among exploitative treatments, maxD was reduced more in CC2 and FDL than CC. However, all three treatments had higher percentages of unacceptable growing stock than selection treatments or commercial clearcutting with rehabilitation. The rehabilitation treatment, despite a narrower range of tree size classes and lower financial return, has characteristics of a High-order cutting practice (Table 1) with regards to intensive management, species composition, and tree quality.

Although this study is not replicated, value is derived from the length of observation and potential for integration within a network of other CPL studies. Implemented across a gradient of landscapes and environmental conditions, CPL studies provide an opportunity to explore regional impacts of long-term silviculture in the Northeast (Adams et al. 2012). Preliminary synthesis of CPL data by Kenefic and Schuler (2008) showed that magnitude of response to recurring management may vary between forests, although cross-region trends were evident. For example, recent findings from the Fernow CPL study confirm the degrading effects of diameter-limit cutting on residual stand quality and value while highlighting species-driven differences in treatment effects on growth (Schuler et al. 2016). A collaborative, network-wide approach to analysis will increase the influence of each individual study and provide greater insight on the role of silviculture in forest sustainability and productivity (Ryan and Swanson 2014, Stine 2014). Such an effort should be the focus of future work.

Supplemental Podcast

This article includes a podcast interview. Visit the online version of this article to listen to the podcast.

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CORRIGENDUM

For. Sci. 64(1):112
doi:10.1093/forsci/fxx021

Rogers, N.S., L.S. Kenefic, M.S. Crandall, R.S. Seymour, P.E. Sendak. Sixty years of silviculture in a northern hardwood forest in Maine, USA. *Forest Science.* DOI:https://doi.org/10.5849/FS-2016-014.

Error was in Figure 1 in the publication of this article that appeared online ahead of print. A description of the error is provided below:

- In Figures 1a–1d, the Y axes were incorrect, such that the number of trees per hectare was too low by a magnitude of four.

Figures 1a–1d showing the correct axes are provided below, and have been updated for print publication.

The correct version of the figure appears in the article by Rogers et al. in this issue. The authors regret the error.