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Tree quality and value: results in northern conifer stands after 65 years of silviculture and harvest

Maren Granstrom, Mindy S. Crandall, Laura S. Kenefic, and Aaron R. Weiskittel

Abstract: Despite the importance of financial outcomes to stand-level forest management decision-making, long-term assessments are rare. We compared the quality and value of mixed, northern conifer (*Picea–Abies–Tsuga*) stands in Maine, USA, treated with a range of silvicultural systems and exploitive cuttings for 65 years. Ten replicated treatments — single-tree selection and uniform shelterwood systems, commercial clearcutting, fixed and guiding diameter-limit cutting, and no cutting — were assessed for quality and value of standing and harvested trees. Selection systems resulted in good tree quality and high stand value, particularly when applied on a short cutting cycle, but small harvest volumes were not always commercially operable. Shelterwood system resulted in good tree quality, but changes in species values over time influenced financial outcomes. In contrast, commercial clearcutting and fixed diameter-limit cutting resulted in poor tree quality and low residual stand value after multiple harvests. Guiding diameter-limit cutting resulted in high stand value and is more appropriately characterized as a silvicultural system than exploitive harvesting when applied with harvest volume limits and seed tree retention. Overall, treatments focused on short-term financial gain led to degraded stand conditions, while those that sought to grow high-quality trees resulted in desirable outcomes over the long term.

Key words: spruce–fir, shelterwood, selection cutting, exploitation, forest management.

Résumé : Malgré l'importance des résultats financiers résultant des prises de décisions en gestion forestière des peuplements, les évaluations à long terme sont rares. Nous avons comparé la qualité et la valeur de conifères septentrionaux sur pied mixtes (*Picea–Abies–Tsuga*) dans le Maine, aux États-Unis, traités avec un éventail de systèmes sylvicoles et de coupes d'exploitation durant 65 années. Dix traitements reproduits — systèmes de coupe progressive uniforme et de jardinage d'arbres individuels, coupes à blanc commerciales, coupes de diamètre limité fixes et générales et absence de coupes — ont été évalués en fonction de la qualité et de la valeur des arbres sur pied et des arbres récoltés. Les systèmes de sélection ont eu comme résultat une bonne qualité d'arbres et une valeur élevée des arbres sur pied, particulièrement lorsqu'ils étaient appliqués à un cycle court de coupes, mais les volumes réduits de récoltes n'étaient pas toujours exploitables sur le plan commercial. Le système de coupe progressive a eu comme résultat une bonne qualité d'arbres, mais les changements dans les valeurs des espèces au fil du temps ont influencé les résultats financiers. Par contre, la coupe à blanc commerciale et la coupe limitée à un diamètre fixe ont eu comme résultat une mauvaise qualité d'arbres et une faible valeur résiduelle des arbres sur pied après de nombreuses récoltes. La coupe de diamètre limité générale a eu comme résultat une valeur élevée des arbres sur pied et elle est caractérisée de manière plus appropriée comme un système sylvicole plutôt qu'une récolte d'exploitation lorsqu'elle est appliquée avec des limites du volume des récoltes et une sauvegarde des semenciers. Dans l'ensemble, les traitements axés sur les gains financiers à court terme ont entraîné des conditions de dégradation des arbres sur pied alors que ceux qui visaient à accroître une qualité élevée des arbres ont mené à des résultats souhaitables à long terme. [Traduit par la Rédaction]

Mots-clés : épinette–sapin, coupe progressive, coupe de jardinage, exploitation, gestion forestière.

Introduction

Forest landowners and managers make decisions about whether and how to manage forests based on a number of short- and long-term considerations. For commercial landowners, return on investment or maintenance of the wood supply stream might be driving factors, while non-commodity values such as recreation or wildlife habitat might motivate other types of landowners (Butler et al. 2016). In all cases, forest management actions have implications for quality and value of harvested trees and the future forest. In a perfect world, decisions about forest management would consider these implications. Yet this information is often lacking, in part because there are relatively few records that allow for robust analysis of long-term outcomes from different silvicultural systems applied in the same forest (e.g., Draper and Froese 2021; Draper et al. 2021). Long-term implications of repeated applications of silvicultural systems are of interest to more than just landowners and managers, however; results such as these can also provide scientific information about forest responses to other types of anthropogenic disturbances.

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Though growth and yield models have been used to predict outcomes of a range of options for a given starting condition, there is uncertainty in the reliability of predictions in structurally and compositionally complex stands (Saunders and Arseneault 2013). Empirical studies, in which responses to treatments are tracked in operational-scale manipulative experiments, are generally regarded as the most reliable basis for silviculture decision-making (e.g., Leak et al. 2014), but data are rare and often incomplete due to lapses in funding and staffing associated with large-scale, long-term studies (e.g., Kenefic and Kern 2013). We are thus fortunate that such records are available from the US Department of Agriculture, Forest Service's Compartment Management Study (CMS) on the Penobscot Experimental Forest (PEF) in Maine, USA. The CMS has continued with replication and without interruption since 1952 and provides a rich opportunity to assess multiple long-term outcomes resulting from silvicultural systems and exploitive cuttings common in the Acadian Forest region where it is located.

Results of the CMS have been reported several times: notably by Frank and Blum (1978) after 20 years and Sendak et al. (2003) after 40 years. Several management recommendations have emerged, including a silvicultural guide for spruce–fir (Frank and Bjorkbom 1973) and a primer on effects of diameter-limit cutting and silviculture (Kenefic and Nyland 2005). These results focused on structure, composition, and growth and yield, but did not attempt to take into account the shifting external market conditions that foresters face when planning and managing over long time frames. Because the CMS was designed to assess real-world forest management decisions typically based in current market conditions or expectations (Luppold and Sendak 2004), it provides a unique opportunity to consider how changing market conditions have influenced the relative performance of each system. While there is now growing awareness that forests provide multiple values beyond monetary income, understanding the implications of alternative silvicultural systems for tree quality and value is still critical for forest landowners and managers, as timber harvest can help support management that favors any number of landowner goals.

This paper expands analysis of the CMS to improve our understanding of the long-term effects of forest management decisions. We do this by incorporating an additional 25 years' data since 40-year results were presented by Sendak et al. (2003), assessing financial outcomes and considering the changing market conditions in which forest managers operate, and applying a wider variety of analytical approaches. We also revisit initial CMS objectives, in recognition that findings often become apparent only through repeated treatment and long-term monitoring and are not always part of the original intent of a study. The goals of our work are to (*i*) assess returns to forest landowners by comparing harvests over 65 years across a range of silvicultural treatments and exploitive cuttings, and (*ii*) determine how these treatments impact long-term stand quality and value. For the first goal, we assessed harvested volume and value by treatment. For the second, we compared metrics of standing tree quality along with tree size-class distribution and value, elements that influence future stand structure and opportunities for returns through harvests.

Methods

Study site

The 1619 ha PEF is located in Bradley and Eddington, Maine (44°52′44″N, −68°39′12″W), in the southern portion of the Acadian Forest, which includes northern Maine, southeastern Canada, and higher elevations of northern New York, Vermont, and New Hampshire (Fig. 1; Rowe 1972). This forest type is dominated by shade-tolerant species, including spruce (primarily red spruce, *Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill.) with components of eastern white pine (*Pinus strobus* L.), northern white-cedar (*Thuja occidentalis* L.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and hardwoods including maple (*Acer* spp.), aspen (*Populus* spp.), and birch (*Betula* spp.). Mean temperatures on the PEF are −7.1 °C in February and 20.0 °C in July, and mean elevation is 43 m above sea level. Mean annual rainfall and snowfall are 106 and 239 cm, respectively. Terrain is fairly flat, and soils range from very poorly drained to somewhat excessively drained, though most of the study area is somewhat poorly to poorly drained. Most soils in the study area are derived from glacial till (76% of permanent sample plots); soils in depressions and along water courses are derived from marine sediment (Natural Resources Conservation Service 2012). The disturbance regime is dominated by small-scale events such as insect mortality causing growth suppression and mortality of individual trees of selected species, and individual tree windthrow or breakage; fire and stand-replacing disturbances are rare to non-existent and have not occurred since the US Forest Service record keeping began. Harvesting history at the PEF is not well documented before 1950, but periodic partial harvesting from at least the 1700s led to an irregular size structure and few trees larger than 30 cm in diameter (throughout this paper, diameter refers to that measured at 1.37 m above the ground) at the time studies were initiated (Sendak et al. 2003).

Treatments

The Forest Service initiated the CMS in 1952 with the objectives of assessing production potential and financial feasibility of multiple silvicultural systems relevant to forest industry (Kenefic et al. 2014). The original emphasis was comparing silvicultural systems — primarily selection but also shelterwood — to exploitive cutting, common at the time of study initiation and still practiced in the region today. Exploitive cutting differs from silvicultural systems in that it focuses on what is removed without intentionally establishing regeneration or creating desired residual stand conditions.

Two stand replicates each of nine treatments, plus an untreated area, were established between 1952 and 1957 in experimental units (called management units, MUs) between 7 and 18 ha in size (replicates of the same treatment were usually established in different years). Each MU was commercially harvested by independent contractors, and stumpage was sold through bid or negotiation. Logging technology used in the CMS included horse logging and cut-to-length systems, but most harvests were conducted with chainsaws and rubber-tired skidders. Records of logging and stumpage sales were archived by the Forest Service but are missing for some MUs and harvests.

The original CMS study plan was written in 1953 and updated in 1962, 1974, and 2008; each iteration included adjustments to prescriptions and measurement protocols. Treatments are described in detail below and in the supplemental material.

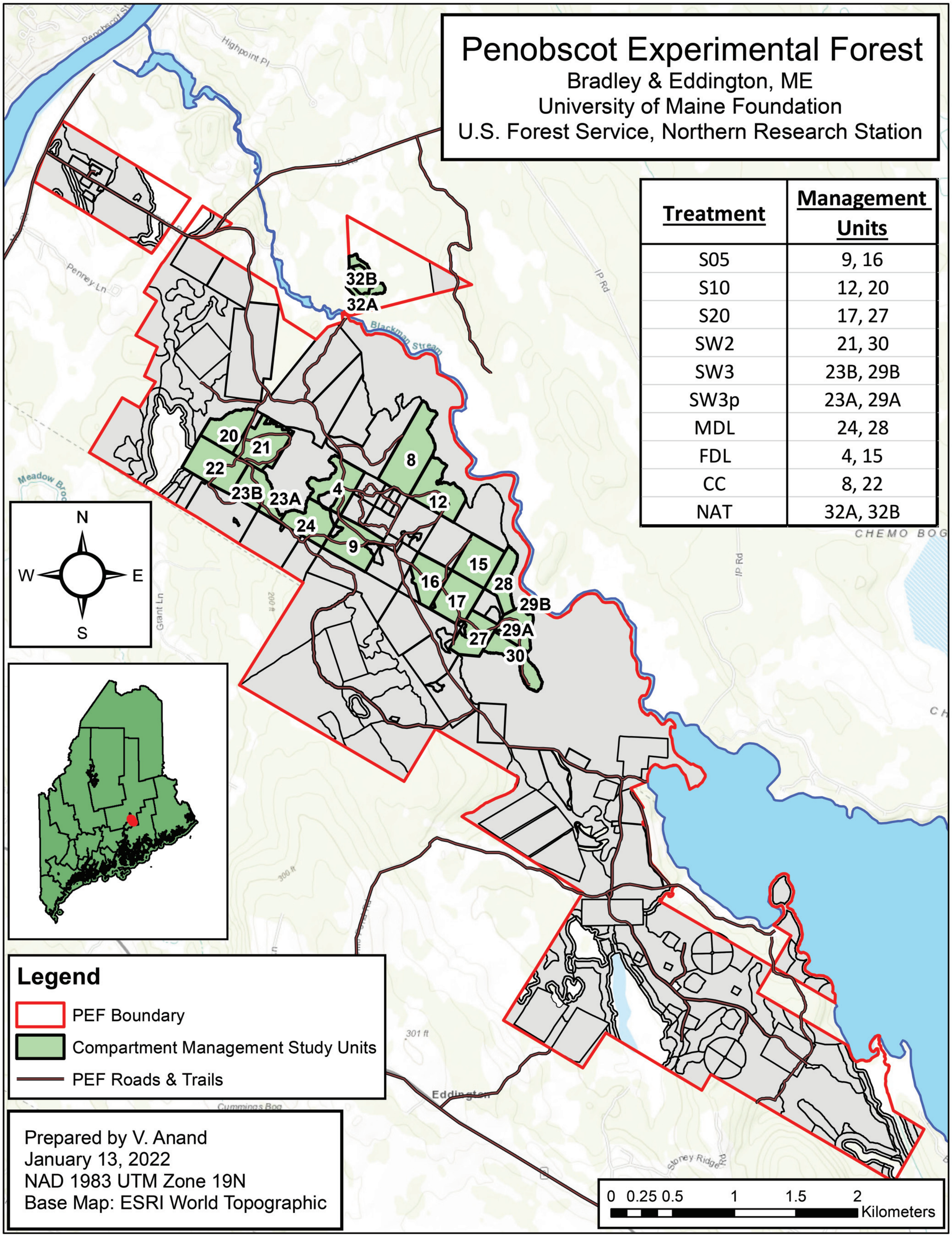
Even-aged silviculture: uniform shelterwood

Two variants of uniform shelterwood were included in the CMS. The two-stage shelterwood (SW2) was established through an initial harvest combining both preparatory and establishment cuts, with an overstory removal 10 years later. Submerchantable trees (<16.5 cm diameter) and some larger trees for which there were no local markets were retained, creating a two-storied structure; commercial thinning was conducted in 2012. The three-stage shelterwood (SW3) utilized three separate entries: an initial preparatory cut, an establishment cut about 10 years later, and a complete overstory removal about 5 years after that. The SW3 MUs were subsequently split in half and one half of each was precommercially thinned in the 1980s (SW3p). The SW3p MUs were commercially thinned in the 2000s for a separate study; our analyses of these MUs ends at that time.

Uneven-aged silviculture: single-tree selection

Single-tree selection system on 5-, 10-, and 20-year cutting cycles (S05, S10, and S20, respectively) was applied with the *BDq* method (Guldin 1991), where *B* is residual basal area (BA), *D* is maximum

Fig. 1. Map of the Penobscot Experimental Forest and the location of the Compartment Management Study units (prepared by V. Anand, USFS Penobscot Experimental Forest). Treatment labels are explained in the Methods section.



residual diameter, and q is the constant ratio between residual numbers of trees in consecutive diameter classes (see supplementary Table 1[1]). Although harvests occurred regardless of standing BA for the first 50 years of the study, those after 2003 were postponed until the next scheduled entry if the difference between pre-cut and target post-cut BA (i.e., allowable cut) was less than a designated amount. This resulted in one skipped harvest in both S05 and S10. In total, there were 12 harvests between study establishment and the analysis year (2019) in S05, six in S10, and four in S20.

Exploitive cutting

In the commercial clearcut treatment (CC, also called logger's choice or unregulated harvest), all merchantable trees were harvested while cull trees (i.e., without a sound 2.4 m log) and those of poor form or undesired species were retained. There have been two harvests in this treatment, first in the 1950s and most recently in the 1980s. The second harvest removed more volume than the first due to changes in merchantability standards. In the fixed diameter-limit (FDL) treatment, all merchantable trees above species-specific diameter limits were harvested every 20 to 25 years beginning in the mid 1950s; cull trees were retained. Diameter limits varied over the study period (supplementary Table 2[1]). These MUs were harvested three times prior to our analysis. A compromise in exploitive systems is found in guiding diameter-limit cutting (also called flexible or modified diameter-limit cutting, MDL), in which allowable cut is constrained to net periodic growth (Guldin and Baker 1998; Miller and Smith 1993). In the CMS MDL treatment, most merchantable trees above species-specific diameter limits were harvested every 20 years starting in the 1950s, with the following constraints: some trees above diameter limits were retained to provide seed or wind protection for the residual stand, some trees below diameter limits were harvested to capture mortality, and an allowable cut was set. These MUs were harvested four times.

Reference

An untreated "natural area" (NAT) was designated in 1954 and serves as a reference for the CMS, although it is not contiguous with the other MUs. In 1993, this area was divided into two MUs based on differences in composition and structure (Sendak et al. 2003). These are neither true replicates nor representative controls; though some results are presented in this paper for comparison, they are not included in statistical analyses.

Data collection

Each MU contains 8 to 21 systematically located permanent sample plots with a nested design consisting of 0.08, 0.02, and 0.008 ha circular plots for sampling trees of ≥11.4, 6.4, and 1.3 cm diameter, respectively; full details of the experimental and sampling design can be found in Waskiewicz et al. (2015). Inventories were conducted every 5 to 10 years as well as before and after every harvest. At each inventory, species, diameter, and status (live, dead, merchantable, and cull) of each in-plot tree was recorded. For five plots within each MU of the S05, SW3, and CC treatments, soil parent material and depth to redoximorphic features were determined from field measurements and laboratory analysis (Puhlick et al. 2016*b*). For other plots, parent material was determined using a second-order soil survey (Natural Resources Conservation Service 2012), and depth to redoximorphic features were determined through field measurements (Olson et al. 2019). These data were used to assign drainage class (Briggs 1994).

Between 2012 and 2015, trees of ≥11.4 cm in diameter were recorded as Acceptable or Unacceptable Growing Stock (AGS or UGS, respectively; Nyland 2016; p. 240) on at least one third of plots in each MU. AGS had at least one sound 2.4 m log and were expected to increase in volume and value, while UGS did not have a sound log or were not expected to increase in volume or value due to risk factors such as damage, decay, structural weakness, or poor vigor (Kenefic et al. 2018).

Gravel roads intersected about 17% (n = 47) of the 0.08 ha plots. For these plots, expansion factors for calculating per-hectare values were adjusted based on amount of overlap with the road as calculated in ArcMap (ESRI 2018). In some cases, the small sample size of the surveyed trees along with the increased expansion factors resulted in adjusted values for stems per hectare or BA per hectare more than two standard deviations from the mean (and outside the biological potential of the site); these nine plots (3% of the total sample) were excluded from analysis.

Data calculations

A model adapted from Robinson and Wykoff (2004) with MU, plot, and species as random effects was used to predict tree heights from 6902 measurements throughout the study area (conditional R^2 = 0.92). Total and merchantable volume were determined with regional species-specific taper equations from Li et al. (2012) and Weiskittel and Li (2012). Trees were considered merchantable with a minimum 11.4 cm diameter, 10 cm stump height, and 10 cm top diameter.

Due to incomplete records of actual stumpage from harvests, harvest revenue was calculated from inventory and published stumpage price data. Harvested volumes were calculated by species as differences between merchantable volumes of live trees in pre- and post-harvest inventories. Estimated pulpwood and sawtimber volumes were multiplied by inflation-adjusted (to 2017 dollars) prices for each species in the year in which the harvest occurred. Stumpage was calculated using price reports from University of New Hampshire Extension from 1950 to 1958 (UNH Extension 2018) and the Maine Forest Service from 1959 to 2017 (Maine Forest Service 2022). These reports do not include all species on the PEF and group spruce–fir as one. Species such as elm (*Ulmus* spp.), black cherry (*Prunus serotina* Ehrh.), and black ash (*Fraxinus nigra* Marsh.), present in very small quantities in the CMS, were grouped with similar hardwoods.

Costs accounted for included marking and precommercial thinning. Marking costs were calculated using equations created at the PEF (Sendak 2002), and represent the time of three workers: one tallying and two measuring and painting trees. Treatment was not found to be important by Sendak (2002), and calculations are based on volume of wood harvested and hourly rate of pay ($13 h^{-1} for student workers in this analysis). Only CC and the final overstory removal of the shelterwood treatments were not marked; marking costs were subtracted from all other harvests. Costs for precommercial thinning, taken from PEF records and adjusted for inflation to 2017 dollars, were subtracted in SW3p.

The sum of calculated stumpage from all harvests, along with appropriate costs, was discounted to 1950 with several rates to simulate the decision of a forest manager comparing alternatives for managing land for financial return. A higher discount rate gives greater preference to harvest returns received closer to the start, in this case 1950. We chose a 6% rate to represent a financially driven investment company, a 4% discount rate as has been used by the Forest Service on national forest lands, and a 2% rate to represent landowners with multiple values.

Stumpage records were available for close to half of the harvests, primarily from 1967 to 1977 and from 2013 to 2018. Records of actual stumpage received and volumes removed were compared to calculations from inventory data (Fig. 2). Inventory-based stumpage and volume calculations tended to be slightly higher and slightly lower, respectively, than values on file. Differences might be related to

[1]Supplementary data are available with the article at https://doi.org/10.1139/cjfr-2021-0279.

Fig. 2. Comparison of calculated vs. actual volume (left panel) and revenue (right panel) from selected harvests. Black line indicates 1:1 ratio.

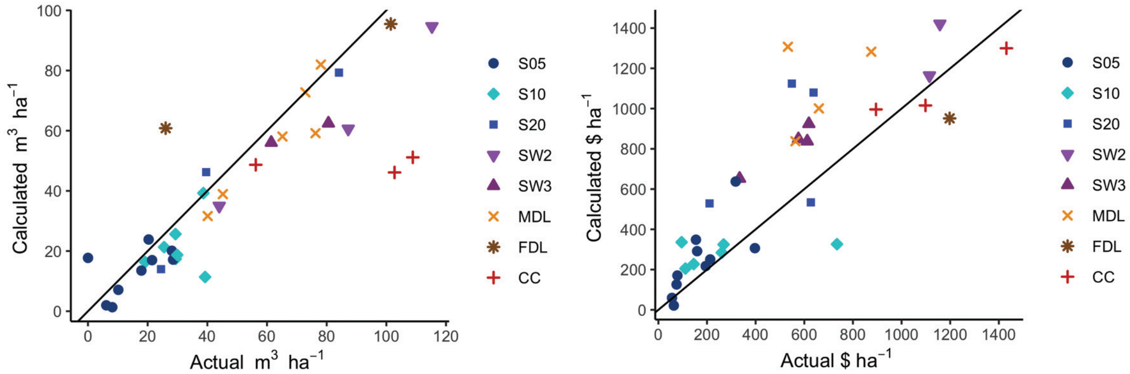


Table 1. Final models for large trees (%BA in live trees ≥30 cm diameter), cull volume (% cull volume ≥11.4 cm diameter), and UGS (%BA in UGA ≥11.4 cm diameter).

Response variable	Explanatory variables ($p < 0.05$)	Marginal R^2	Conditional R^2	RMSE (%)
Large trees	Treatment, years, treatment×years, HI, %large_start	0.64	0.65	1.56
Percentage cull	Treatment, years, treatment×years, HI, elevation, %cull_start	0.35	0.35	3.38
Percentage UGS	Treatment	0.40	0.95	1.69

Note: Random effects were management unit (MU) and plot-within MU. Explanatory variables included ($p < 0.05$) treatment; years, number of years since study start; HI, harvest index; elevation, mean elevation of plot; %cull_start, percentage of volume in live trees >11.4 cm diameter that were classified as cull before treatments began; and %large_start, percentage of BA in live trees that were >30 cm diameter before treatments began. UGS, unacceptable growing stock; BA, basal area; RMSE, root-mean-square error.

sampling error associated with plot- versus stand-level data, but variability in local markets is important. For example, in Penobscot County (where the PEF is located) the price of spruce–fir in 2010 ranged from \$15 to \$200 mbf^{-1} (Maine Forest Service 2022). Because of uncertainty associated with these calculations, stumpage data were not tested for statistically significant differences among treatments.

Statistical analysis

Percentages of BA in large trees (≥30 cm diameter), UGS BA, and cull volume were compared among treatments using linear mixed-effects models, with repeated measures when applicable. Additional plot-level covariates tested for inclusion were soil parent material (marine sediment, glacial till, organic, or alluvial) and drainage class, mean elevation in the 0.08 ha plot based on a 1 m digital elevation model (UNB Forest Watershed Research Center 2014), and harvest index (a score based on volume harvested and years since harvest; Puhlick et al. 2016*a*). Time (number of years since the first inventory in each MU) was included as a fixed effect and tested as an interaction with treatment. Pre-treatment condition, i.e., the value of the response variable at the first inventory, was tested for model inclusion to account for variation among plots or MUs. Parent material and drainage class were correlated and potentially confounded, so were tested separately for inclusion in models; parent material was not included in any final models. MU and plot-within MU were included as random effects, and potential spatial autocorrelation was accounted for by including latitude and longitude of each plot. Models were created using the lme function in the nlme package (Pinheiro et al. 2019) in R version 3.5.1 (R Core Team 2018). Models were selected based on the lowest corrected Akaike information criterion (AICc) value with all variables significant at the 0.05 level. When AICc values were ±5 in different models, the more parsimonious model was chosen.

Harvested volume (total, pulpwood, and sawtimber), standing tree size-class distribution (sapling, pole, and sawtimber BA), standing tree quality (percentage cull volume and UGS BA), and value of standing and harvested trees were compared among treatments. Pairwise differences were assessed using the emmeans and cld functions in the emmeans (Lenth 2019) and multcomp packages in R; differences were considered significant at the 0.05 level. Results of models with repeated measures are presented at the study midpoint (about year 30) and most recent inventory (about year 65).

Results

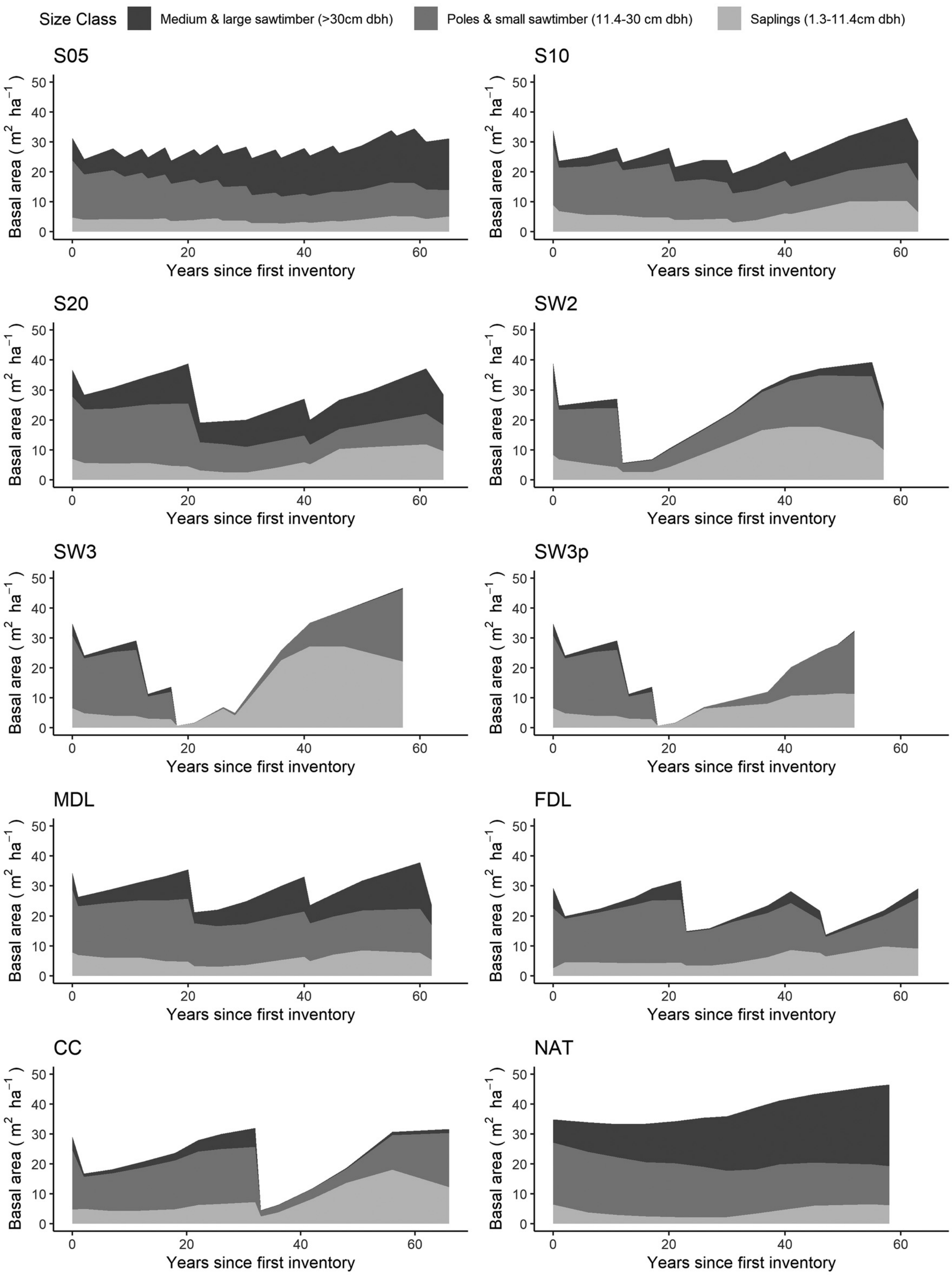
Harvested volume

Timing and intensity of harvests differed among treatments based on prescriptions in the CMS study plan (Fig. 3). Volume removed in each harvest, as well as the percentage of harvested volume that was sawtimber, varied over time with relatively lower percentages of large trees in later harvests in FDL and CC (Fig. 4). Yet total merchantable harvested volume over the 65-year study period did not differ significantly among treatments (supplementary Table 3[1]).

Standing tree size and composition

There was a significant interaction between the effects of treatment and time on percentage BA in large trees (i.e., medium and large sawtimber) (Table 1; Fig. 3). When compared at the study midpoint, percentage BA in large trees was significantly greater in the selection treatments and MDL than shelterwoods, CC, or FDL (Fig. 5; supplementary Table 4[1]). The same differences were observed at the most recent inventory, though FDL also had a greater percentage of BA in large trees than shelterwoods or CC at that time. With regard to composition, we found that selection treatments and MDL maintained spruce and hemlock over time, while those species decreased — and hardwoods and fir increased — in CC (Fig. 6). Notably, composition of SW3p was dominated by spruce–fir at the most recent inventory; other treatments had relatively greater proportions of other species.

Fig. 3. Basal area over time of live trees by size class: saplings (light grey), poles and small sawtimber (medium grey), and medium and large sawtimber (dark grey) for all treatments.



Standing tree quality

Percentage UGS BA was significantly greater in CC and FDL than S05 (Table 1). In fact, mean percentage UGS BA was more than twice as high in FDL and CC than any other treatment (Fig. 7). Percentage cull volume also differed by treatment, with a treatment by time interaction (Table 1). Percentage cull volume was significantly greater in FDL, MDL, CC, and SW2 than S05, S10, SW3, or SW3p at study midpoint. At the most recent inventory, FDL had a higher percentage of cull volume than every treatment except MDL and CC, and selection treatments and SW3p had significantly less percentage cull than CC, MDL, or FDL. Observed means of percentage cull volume over time (Fig. 8) suggest that while selection treatments and SW3 reduced it and kept it low, in MDL, FDL, CC, and SW2 it was higher but varied over time.

Fig. 4. Observed mean calculated harvest volumes (bars, left axis) for each harvest, and percentage of harvest volume in sawtimber (blue line, right axis) for all treatments. Number of harvest entries and time between harvests varied by treatment according to the Compartment Management Study plan.

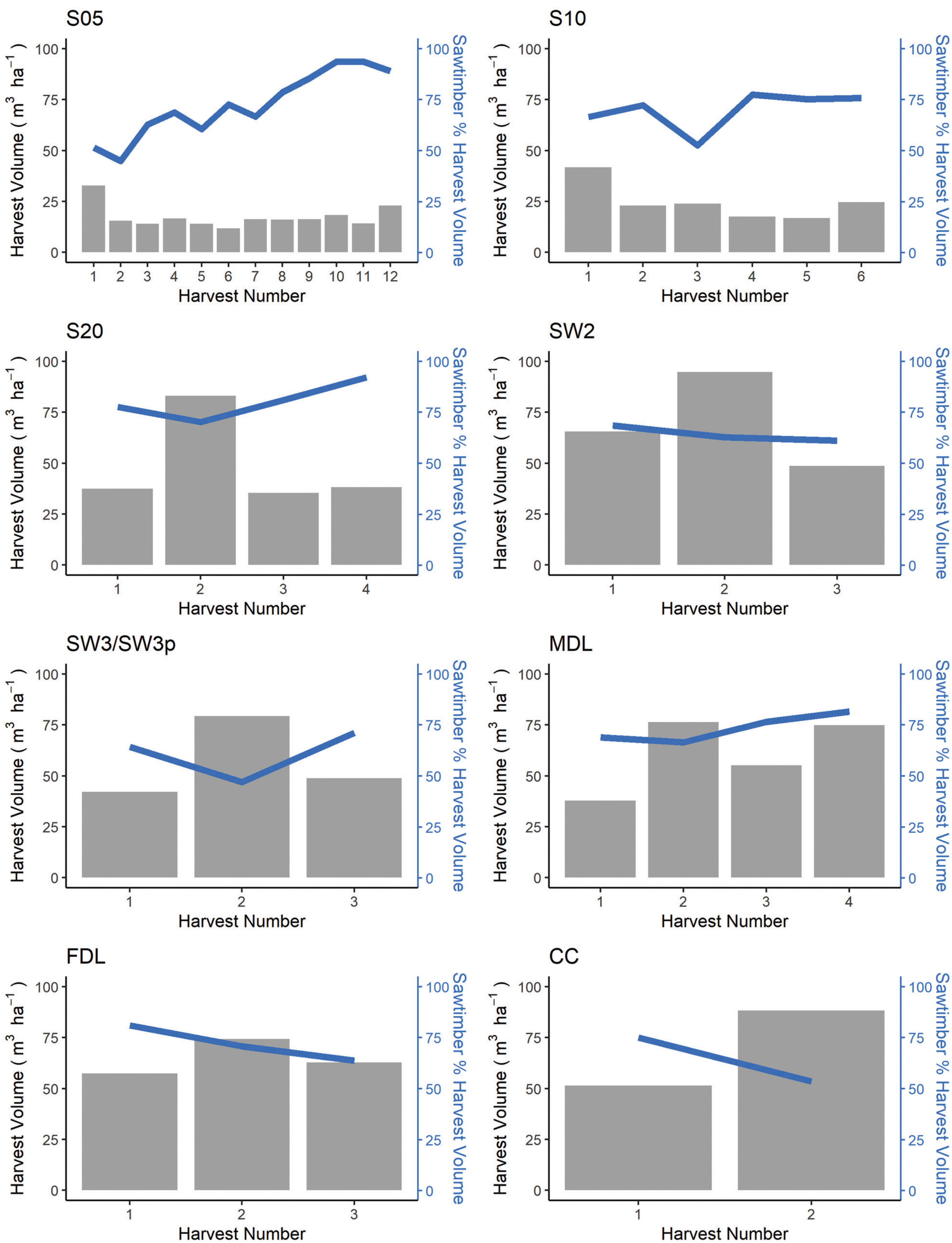


Fig. 5. Observed mean percentage of basal area (BA) in live trees ≥30 cm diameter over time, by treatment.

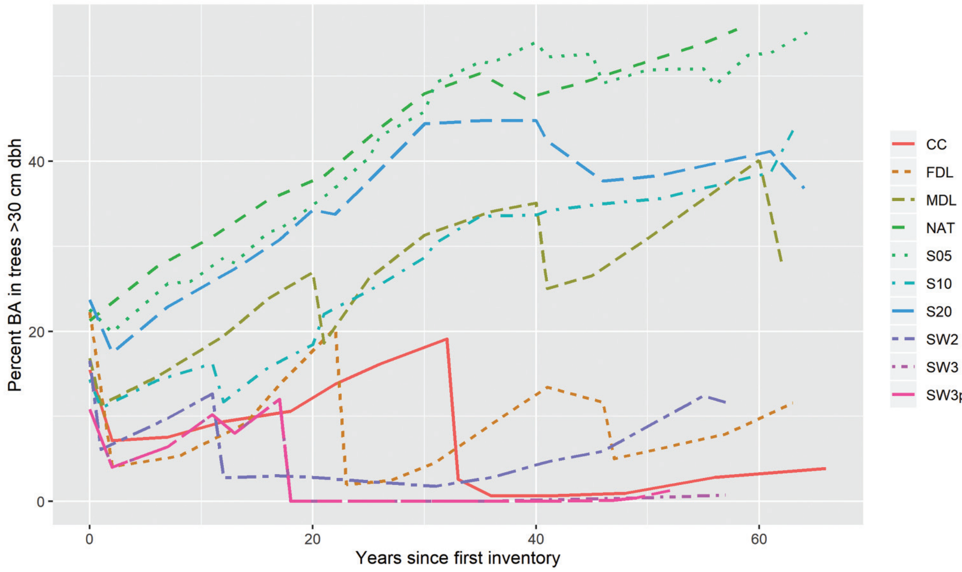


Table 2. Mean calculated value of harvested timber and standing stumpage (\$ ha^{-1} in constant 2017 dollars, approx. 1953 to 2018), and harvest values discounted to 1950 with 2%, 4%, and 6% rates.

Treatment	Standing value at start (a)	Stumpage value, all harvests (b)	Standing value, most recent inventory (c)	Stumpage and standing (total) value (d)	Total value minus starting value (d − a)	Discounted harvest value (b), 2%	Discounted harvest value (b), 4%	Discounted harvest value (b), 6%
S05	1835 (324)	2947 (259)	3203 (162)	6150 (421)	4314 (745)	1490 (63)	877 (151)	583 (163)
S10	1758 (109)	2116 (167)	2920 (74)	5036 (419)	3278 (327)	1238 (125)	845 (104)	635 (91)
S20	2029 (230)	2878 (234)	1837 (134)	4715 (368)	2686 (138)	1550 (245)	961 (231)	662 (210)
SW2	2001 (169)	2997 (486)	1024 (19)	4021 (467)	2020 (298)	1950 (229)	1427 (138)	1109 (98)
SW3	1758 (179)	2205 (203)	1664 (605)	3869 (402)	2110 (581)	1592 (120)	1178 (72)	893 (44)
SW3p	1758 (179)	1373 (203)	1898 (271)	3271 (68)	1513 (247)	1150 (120)	941 (72)	764 (44)
MDL	1954 (207)	3771 (176)	1761 (28)	5532 (208)	3578 (412)	1813 (67)	1041 (46)	687 (48)
FDL	1670 (73)	2853 (584)	942 (76)	3794 (659)	2124 (587)	1765 (363)	1223 (266)	922 (211)
CC	1420 (258)	2001 (12)	876 (231)	2877 (243)	1457 (15)	1318 (131)	957 (173)	751 (186)

Note: Estimated marking and precommercial thinning costs have been deducted from harvest totals, where applicable. Standard errors are in parentheses.

Value

The undiscounted sum of calculated stumpage from all harvests (Table 2) was highest in MDL, followed by SW2, S05, S20, and FDL, and lowest in CC. The value of standing timber at the most recent inventory was highest for S05; the value of harvested plus standing timber was highest in S05, followed by MDL, S10, and S20. Even when starting value is subtracted to account for variability in pre-treatment condition, harvest plus standing value was lowest in CC. When harvest revenue (not including standing value) was discounted to 1950, the highest returns at 4% and 6% rates were from SW2 (Table 2). At the 6% rate, CC surpassed selection treatments, but not shelterwoods or FDL. At the more conservative 2% rate, all treatments except S10 remained higher than CC.

Discussion

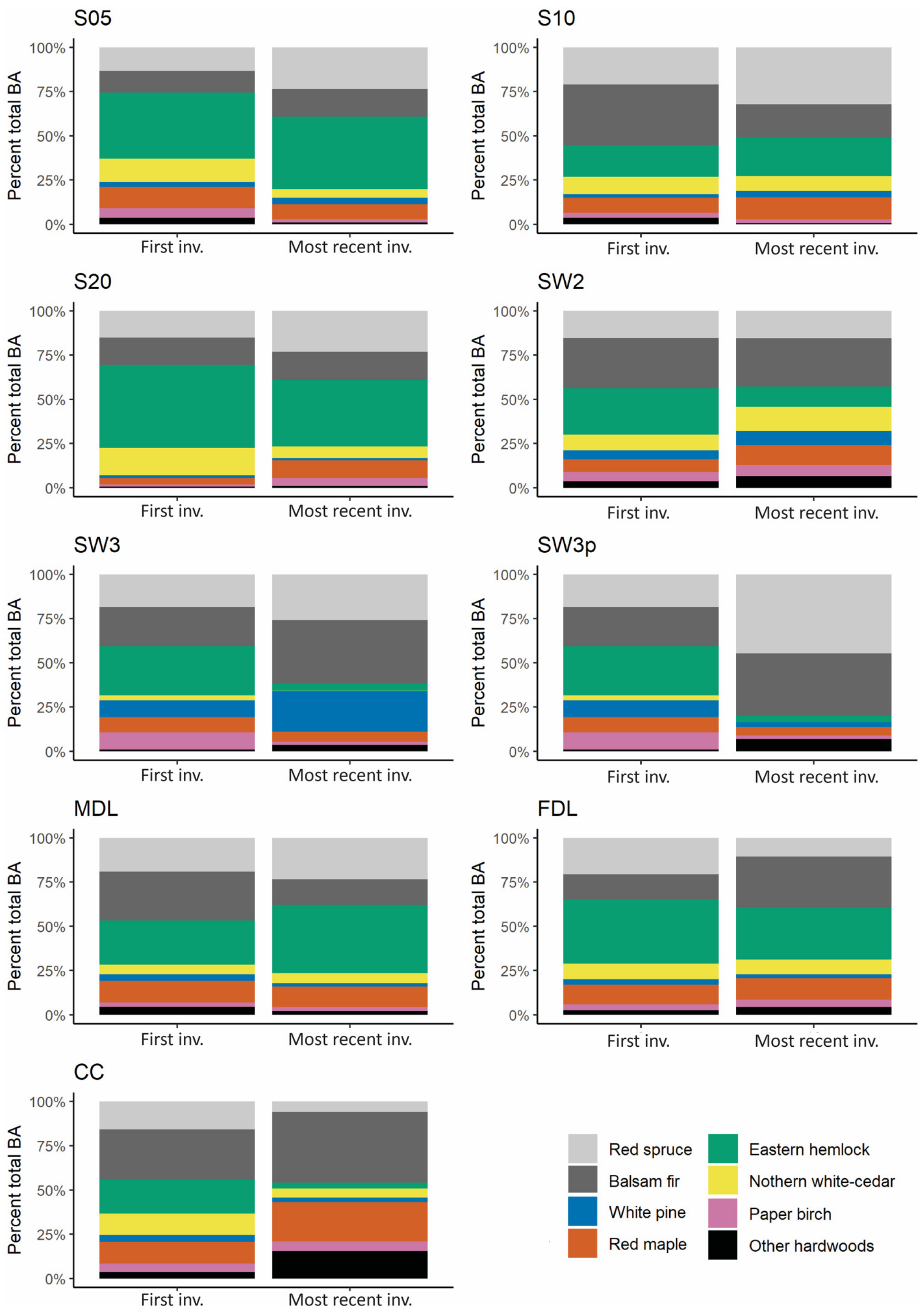
The focus of this paper is the quality and value of harvested trees and residual stands across a variety of treatments over 65 years. Because a forester will rarely see results of their management decisions decades in the future, long-term studies like this one can help them anticipate treatment outcomes and make decisions that benefit both the forest and landowner. While the results of long-term research help explain those outcomes, the process of long-term research is also important, as it highlights changing priorities and growing knowledge.

While site-specific variables such as accessibility and harvest block size influence harvest revenue, the financial value of a stand is based largely on quality and size of trees, and the presence of species that are valuable in current markets. Similar to Draper et al. (2021), who reported 65-year results from a northern hardwood silviculture experiment in Wisconsin, USA, we found that volume and value of trees harvested over time and residual stand quality were influenced by the type of silvicultural treatment or exploitive cutting applied. Yet total volume harvested did not differ significantly by treatment in our study (supplementary Table 3[1]), so it was the timing and characteristics of the harvests that created differences in quality and value. This is an important result, as exploitive cutting is often motivated by the perception that such a course of action maximizes returns to the landowner (Kenefic and Nyland 2005). While that might be true in the short run, it does not necessarily bear out in the long term, and exploitive harvests have implications for residual tree quality and value.

Tree quality

A critical indicator of future stand value is volume of poor-quality trees, measured here as percentage UGS and cull. SW3 and SW3p had a complete overstory removal as part of the establishment process; this eliminated all trees of merchantable size, including cull. Selection treatments deliberately sought to remove poor-quality trees first and retain and release the best. As a result, selection and

Fig. 6. Observed mean percentage basal area (BA) (live trees >1.3 cm diameter) by species, at first and most recent inventories, for all treatments.



three-stage (uniform) shelterwood treatments reduced cull volume to near zero within 20 years (Fig. 8); cull remained low in subsequent decades. Cull volume in the exploitive treatments and SW2 was higher and more variable over time. FDL had a significantly higher percentage cull volume than CC, as more and larger poor-quality trees were left. The overstory removal that established SW2 also left unmerchantable trees, contributing to higher percentage cull volume until the new cohort reached merchantable size. Although variability in percentage cull volume over time (Fig. 8) is in part a function of measurements being taken immediately before or after harvests (e.g., cull trees were left in FDL and CC, so percentage cull volume went up after harvests), our overall result is in keeping with Schuler et al. (2017), who found that diameter-limit cutting resulted in lower tree quality than selection or commercial clearcut treatments after 60 years in a mixed mesophytic forest in West Virginia, USA.

Trees considered UGS are not necessarily cull, but similar trends are apparent. Percentage UGS BA was highest in FDL and CC (Fig. 7), and significantly lower in S05 where the prescription calls for attention to retaining the best growing stock, those trees most likely to remain healthy until the desired harvest size, increase in volume and value, to contribute seed and genetic material to the future stand. These results align with those of Rogers et al. (2018), who analyzed a different experiment and data from the PEF and

Fig. 7. Observed mean Unacceptable Growing Stock as a percentage of basal area (BA) in live trees ≥11.4 cm diameter approximately 60 years after the initial treatment. Standard error bars shown on plot calculated from mean of values in each management unit. Letters indicate significant differences by treatment in the same inventory.

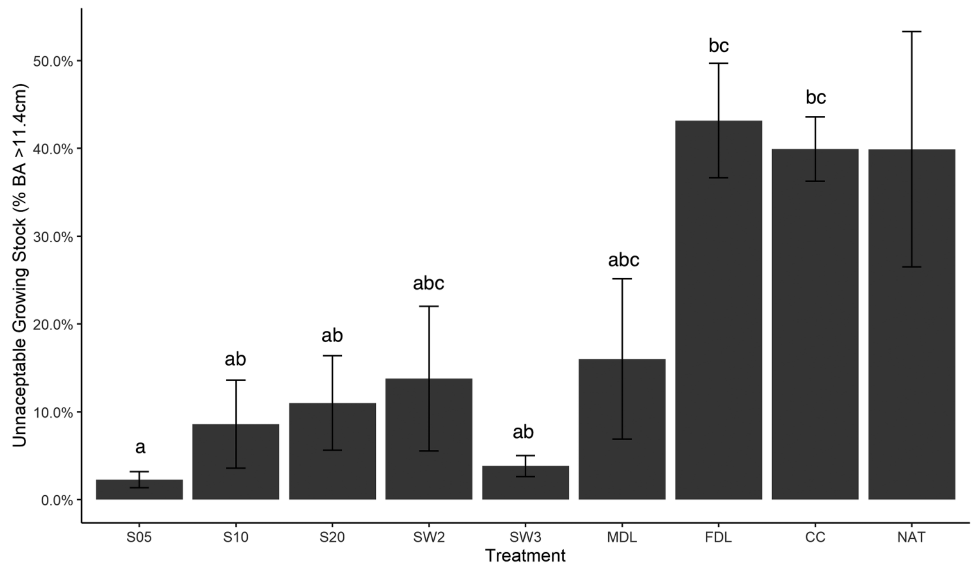
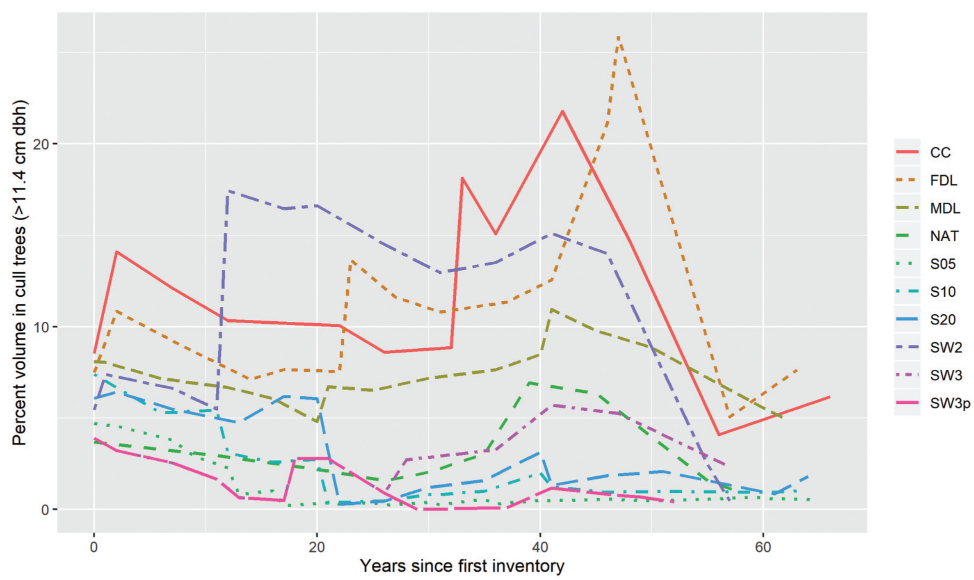


Fig. 8. Observed mean percentage volume in merchantable cull trees over time, by treatment.



found that single-tree selection systems had lower percentages of UGS than FDL or CC after 60 years in northern conifers. In northern hardwoods, Draper and Froese (2021) and Draper et al. (2021) also found that diameter-limit harvesting with low size thresholds (similar to FDL and CC in the present study) failed to produce consistent yield of high-quality trees.

As sawlogs are worth more than pulpwood, and the price of sawtimber has been increasing in recent decades (UNH Extension 2018; Maine Forest Service 2022), size is an important indicator of stand value. Tree size, measured as percentage BA in trees >30 cm diameter, showed clear trends in each treatment over time (Fig. 5). Selection treatments and MDL had generally increasing percentages of large trees, while shelterwoods, FDL, and CC had fewer large trees at the midpoint and most recent inventories than at the time of study initiation (Fig. 5). These results are similar to those of Draper and Froese (2021) and Draper et al. (2021), who found fewer large trees in exploitively harvested northern hardwood stands than in stands managed with silviculture for 60–65 years. Based on prescriptions and cutting cycles, we would expect that the uneven-aged treatments at the PEF, including selection, MDL, and FDL, would maintain these trends in the future. The shelterwood treatments could have a high percentage of trees >30 cm diameter in the future; the maximum size realized will depend on final rotation age. Because CC is fundamentally opportunistic in nature, trees are likely to be harvested before reaching a large size; the proportion of the forest in small trees is a structural characteristic likely to persist over time in those stands.

Another critical component of stand value that changes over time is species composition. In the 1950s and 1960s, there was concern in the Acadian Forest region that poor cutting practices would lead to a shortage of spruce–fir wood supply (McLintock 1962). Researchers set out to demonstrate the silvicultural and financial benefits of a range of management alternatives focused on spruce–fir production. However, changes in demand in regional markets have resulted in hardwoods and sawtimber becoming more valuable than spruce–fir pulp in recent decades (Maine Forest Service 2022). The impacts of changes in demand (i.e., pulp mills closing) can be localized and difficult to predict, as they include both global shifts and local events (Crandall et al. 2017).

Treatments had varied success in meeting species-specific objectives. Increasing spruce and reducing hemlock was, and likely still is, a financially sound decision based on markets over the past 60 years and the northward spread of the hemlock woolly adelgid (*Adelges tsugae*). Selection treatments which created small canopy gaps only did not reduce the percentage of very shade-tolerant hemlock but did at least maintain the percentage of spruce. Three-stage shelterwood treatments, on the other hand, greatly reduced hemlock through heavier cutting and greater manipulation of light. In addition, SW3 increased the percentage of white pine (Fig. 6), and with time those stands may contain valuable sawtimber ready for another shelterwood regeneration treatment capable of producing high financial returns. White pine was less valuable when the precommercial thinning was conducted in SW3p (Maine Forest Service 2022) than it is today and was selectively reduced in that treatment.

Spruce remains desirable for both commodity and non-commodity reasons. SW3p was the only treatment with a meaningful increase in percentage spruce BA, likely as a result of the careful species control through harvest, regeneration, and stand tending treatments when applied. Percentage spruce decreased in FDL and CC over the study period, though this was not a statistically significant result (Fig. 6; Granstrom 2019). Notably, red maple (*A. rubrum*) and other hardwoods were abundant in CC at the most recent inventory. This is consistent with trends in the statewide inventory in Maine, which show decreases in spruce and increases in hardwoods in recent decades (McCaskill et al. 2016). Red maple, with its tendency toward poorly formed stump sprouts in harvested stands, is not always desired for commodity production (Kenefic et al. 2014). While hardwood pulpwood and sawtimber were worth more in the last decade than earlier in the study, the poor quality and small size of trees in CC meant that it still had lower dollar value at the most recent inventory.

Tree value

Realized value from harvest incorporates more than tree quality, size, and species. Stumpage revenue also depends on the time, location, and even personal connections between logger or landowner and wood buyer, and is therefore difficult to predict or replicate across landowners, locations, and years. For example, a harvest in S10 in 2019, when compared with one in 1966, removed 7% more volume (and 12% more sawtimber) but had a 35% higher stumpage value (supplementary Table 3[1]). Markets dictate not only what is cut, but also what is grown in hopes of future profit. Assessing financial outcomes of these treatments will make most sense in the context of changing wood markets.

There have been both general trends and sudden shifts in price over the past 65 years. Prices of sawtimber and pulpwood in the region changed dramatically since the 1950s. The overall price of sawtimber increased for all species analyzed except hemlock, although the price of spruce–fir and aspen fell dramatically in 2017. Pulpwood prices increased in the 1990s and 2000s, but the price of spruce–fir pulpwood fell to its lowest point yet in 2017, and for the past several years has been lower than the price of hardwood pulpwood. Each of these shifts influenced which species and products were deemed desirable for harvest or retention. In current markets, hemlock is less valuable than most hardwoods, but this was not the case for the first several decades of this study (UNH Extension 2018; Maine Forest Service 2022).

Selection cutting on a 5-year cycle had the highest sum of calculated harvest stumpage revenue and standing stumpage of any treatment investigated, even with estimated marking costs subtracted. Similarly, Rogers et al. (2018) compared value in 5- and 15-year selection, FDL, and CC treatments and found that the highest cumulative value resulted from 5-year selection. These results differ from those of Draper et al. (2021) for northern hardwoods; they found that selection cutting with low residual stocking (associated with a longer cutting cycle in our study) was the most favorable in terms of return on investment and residual stand quality. In the present study, percentage of harvested volume composed of sawtimber showed an increasing trend in S05 over time (Fig. 4). With overall prices for sawtimber increasing relative to pulpwood, increasing sawtimber harvests proved beneficial.

An important limitation with S05 as a system is that very light frequent harvests might not be financially or logistically feasible for most landowners. Indeed, our calculations of S05 harvest revenues were high relative to actual values on file (Fig. 2), likely because higher per-volume logging costs reduced stumpage revenue from such small harvests. One scheduled harvest was skipped in both S05 and S10, as the harvestable volume based on the prescription was too low to be feasible using criteria outlined in the study plan (Kenefic et al. 2015). In addition, the percentage of stumpage lost to calculated marking costs in S05 exceeded 20%, though this is based on student workers (likely slower but less expensive on an hourly basis than professionals). Nevertheless, even with a small volume to mark, there is a fixed cost to timber marking and harvest that impacted S05 harvest values.

There are advantages to fewer, heavier harvests. Percentage of stumpage lost to marking costs was much lower in S20 than S05 and the larger volumes removed in each harvest might make this more financially feasible for some landowners. In addition, S20 had slightly better returns than S05 and S10 when discount rates were applied; this is in line with the findings from Draper and Froese (2021) and Draper et al. (2021), who observed better financial return from selection cutting with low residual BA in northern hardwoods. Niese et al. (1995) also compared harvest intensities of single-tree selection in northern hardwoods and found that while the low-intensity harvest improved stand quality, it was too light to provide adequate financial returns for most landowners; medium and heavy selection treatments provided a better balance of income and residual value. Estimated standing stumpage value at the end of the measurement period in the CMS was lower in S20 than S05 or S10, likely due to a heavy recent harvest that reduced the number of large trees. The variability in cutting cycle among treatments, and time elapsed between the last cut and most recent measurement, undoubtedly affected our results. If comparisons were made just before harvest, not just after, volume and stumpage values would differ.

The early overstory removal and heavy commercial thinning (40% of BA ≥11.4 cm diameter) in SW2 resulted in high calculated harvest returns. When assessing financial performance of treatments with all discount rates, SW2 outperformed the others in terms of harvest revenue. However, the recent commercial thinning reduced estimated standing stumpage value to well below three-stage shelterwood, selection treatments, or MDL. Three-stage (uniform) shelterwood had better returns than selection treatments when discount rates were applied, but the even-aged condition resulting from SW3 — consisting of mostly sapling and pole-sized softwood trees — limits opportunities for harvest in the near future. The current low price of softwood pulpwood would make a commercial thinning difficult at this time, and small crowns and high height to diameter ratios (Kenefic et al. 2015) mean that opening these stands could make them susceptible to windthrow (Ruel 1995). In SW3p, precommercial thinning created stand conditions suitable for commercial thinning in the early 2000s (data not shown); this corresponded with a period of high spruce–fir pulpwood prices and would not have been possible a decade later. This result highlights how changing values for particular species or products influences the overall financial performance of a system with little structural or species diversity when viewed from a long-term perspective rather than a moment in time. Results from commercial thinning in spruce–fir stands with previous precommercial treatments indicates that they can increase maximum net present value and reduce the age when maximum net present value is achieved (Hiesl et al. 2017). Importantly, our results show that thinning allows for greater species control and the ability to direct the stand to more desirable, long-lived species such as spruce (see SW3p, Fig. 6).

Commercial clearcutting had the lowest calculated harvest revenue, even with no marking costs, and the lowest estimated standing stumpage value at the end of the study period. Even with all harvests discounted with a 6% rate to 1950, revenue was still higher in SW2, SW3, and FDL than in CC. Even when accounting for its relatively low starting value, CC still had the lowest net gain in value (the sum of calculated harvest and standing stumpage minus the stumpage value at the start; Table 2). Though this practice is thought to be motivated by a landowner's desire to maximize short-term revenue (Gunn et al. 2019), financial performance over the long term in the present study is poor relative to some silvicultural systems. This finding is consistent with Rogers et al.'s (2018) assessment of the financial outcomes of CC and silviculture in northern conifers. Exploitive cutting, including commercial clearcutting, remains common in some parts of northern New England and New York (Belair and Ducey 2018), making findings such as these not only relevant but critical to understanding forest management outcomes across the region.

In FDL, the percentage of sawtimber to pulpwood decreased with each harvest (Fig. 4), as large trees failed to re-grow between harvests. The FDL treatment uses species-specific diameter limits (ranging from 5 to 11 inches) that substantially reduced maximum diameter in the residual stands. As a result, medium- to large-sawtimber rarely regrew during the 20-year interval between harvests. In addition, work by Sokol et al. (2004) on the PEF found that residual trees in the FDL stands were smaller and slower growing throughout their lives compared to those of the same age in other stands. This suggests a dysgenic effect of FDL that may negatively impact tree growth, particularly when coupled with high inter-tree competition due to the lack of tending. In a more limited analysis, Kenefic et al. (2005) found that average value per tree in FDL declined over time compared with S20; while tree values in the first harvest were similar, average per-tree value in FDL was less than half that in S20 by the third harvest. We found that FDL performed better financially than CC, with calculated harvest revenues similar to S05, S20, and SW2 (Table 2). In northern hardwoods, Draper and Froese (2021) found that commercial clearcutting (presented as FDL with a 13 cm diameter threshold) performed more poorly than FDL with a higher removal threshold; they found favorable outcomes from FDL with a 41 cm threshold. These findings differ from those of Nyland (2005), who predicted that harvest revenues would be lower from FDL than selection system after multiple entries in northern hardwoods. Differences between those studies and ours are likely related in part to effects of exploitive harvesting on grade (and thus value) of harvested and residual northern hardwood trees; grade is less influential in conifer-dominated stands like those in the CMS. Nevertheless, estimated current standing stumpage value in FDL in the CMS was lower than all other treatments except CC, even though it has been over 30 years since the last harvest. Rogers et al. (2018) also found lower standing value in FDL than silvicultural treatments after repeated harvests in northern conifers. In northern hardwoods, Niese et al. (1995) found higher harvest returns in FDL than in selection treatments, but negligible residual value after multiple diameter-limit harvests.

A comment on guiding diameter-limit cutting

Though modified diameter-limit cutting (MDL) was included with FDL and CC as an "exploitive" treatment in the CMS study plan, it has marked differences as implemented on the PEF. The inclusion of seed tree retention, higher diameter limits in later harvests, limit of harvesting to no more than net periodic growth, and allowance for marking trees below diameter limits to capture mortality produced comparatively good outcomes from a forest management perspective. In fact, MDL has been promoted for central hardwoods and southern pine as an easier-to-apply alternative to selection silviculture (Miller and Smith 1993; Guldin and Baker 1998). It had the highest calculated harvest revenue of any treatment in the CMS, though standing value was lower than that of the selection treatments despite recent harvests in all. Further investigation of MDL is warranted to determine whether it is a suitable alternative to selection systems for uneven-aged northern conifer stands.

Conclusion

The opportunity to assess nine treatments across a spectrum of management from single-tree selection and uniform shelterwood to diameter-limit and commercial clearcutting at one location over a 65-year period is rare. In light of shifting markets and management goals, as well as continued exploitive harvesting in the region (Belair and Ducey 2018), updated findings and interpretation of long-term studies remain important for today's forest managers. This study will grow in depth as measurements continue in the future. It has become clear that our results depend to some extent on the point at which each treatment is assessed. Future analyses that encompass the second shelterwood harvest, or a third commercial clearcut, may strengthen our results and lead to clearer comparisons. However, a novel climate and increased pests and diseases will create increased management challenges and potentially shift which results are desirable in this forest type. We will continue to gain insights by following this study through a changing lens, and by comparing it with long-term studies elsewhere.

A key finding of the present study, and a key difference between true silvicultural systems and exploitive ones, is that the short-term financial returns from harvests that fail to pay attention to residual stand quality (i.e., exploitive harvesting or high-grading) are not necessarily sustained with repeated application, while the long-term stand and potential value outcomes were maintained with careful stand tending and the attention to the future that is built into silvicultural systems (selection or shelterwood). We found this to be true even though harvested volume did not differ among treatments over the long term. This finding underscores the importance of considering the nuances of silvicultural treatment — the effect of harvests on tree size, species, and merchantability — when deciding whether and how to manage forests. Systems which retain a focus on the future forest, both in terms of regeneration and the next round of harvesting, performed better. This is an important result in light of the perception that exploitive harvesting provides the maximum harvest revenue to the landowner; our results show greater long-term potential from management with a future focus. While these results are specific to the conifer-dominated Acadian Forest region, they confirm observations from studies in other forest types, highlighting the importance of good forest management regardless of species silvics (e.g., Niese and Strong 1992; Draper et al. 2021). This is true not only from a foresters' perspective, but also from that of the landowner seeking to maintain sustainable management flexibility, opportunity, and options over a long term for themselves and their successors.

Competing interests

The authors declare no competing interests.

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Data availability

The Penobscot Experimental Forest permanent sample plot data (https://doi.org/10.2737/RDS-2012-0008-2; https://doi.org/10.2737/RDS-2018-0060), plot-level soils data (https://doi.org/10.2737/RDS-2019-0016), and plot and road location data (https://doi.org/10.2737/RDS-2014-0008-2) used in this publication are available for download with metadata and supplemental files from the US Forest Service, Research Data Archive (https://www.fs.usda.gov/rds/archive/).

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