Silviculture affects composition, growth, and yield in mixed northern conifers: 40-year results from the Penobscot Experimental Forest

Paul E. Sendak, John C. Brissette, and Robert M. Frank

Abstract: This long-term experiment in Maine, U.S.A., was designed to provide information on the best silvicultural practices for managing stands of mixed northern conifers in northeastern U.S.A. We evaluated growth and yield and changes in species composition, quality, and structure during the first 40 years of the experiment. Replicated treatments include the selection system, uniform shelterwood, unregulated harvesting, and diameter-limit cutting. The new cohort established under three-stage shelterwood was subsequently left untreated or precommercially thinned. Between-treatment differences in net volume growth were not significant ($\alpha = 0.10$), though gross volume growth differed significantly for managed vs. unmanaged, selection vs. shelterwood, and shelterwood vs. diameter-limit treatments. A three-stage shelterwood method with precommercial thinning 10 years following final overstory removal resulted in good control of hardwoods and hemlock and a dramatic increase in spruce and fir. The selection system on a 5-year cutting cycle resulted in increased hemlock, spruce, and fir, with a decrease in hardwood species. If the primary goal were production, even-aged management would most likely be preferred. We recommend a two-stage shelterwood method as applied in this experiment with some modification to improve species composition and stand quality. Stand quality (proportion of stand volume in cull trees) and species composition was influenced by treatment.

Résumé : Cette expérience à long terme établie dans le Maine, aux États-Unis, a été conçue pour obtenir de l'information sur les meilleures pratiques sylvicoles pour aménager les peuplements mélangés de conifères nordiques du Nord-Est des États-Unis. Nous avons évalué la croissance et le rendement ainsi que les changements dans la composition, la qualité et la structure des espèces pendant les 40 premières années de l'expérience. Les traitements répétés incluent la coupe de jardinage, la coupe progressive uniforme, la récolte sans contraintes et la coupe au diamètre limite. La nouvelle cohorte qui s'est établie avec la coupe progressive à trois étapes a par la suite été laissée sans traitement ou a subi une éclaircie précommerciale. Sur la base de la croissance nette en volume, les différences entre les traitements n'étaient pas significatives ($\alpha = 0,10$) quoique la croissance brute en volume différait significativement entre les traitements avec et sans aménagement, entre la coupe de jardinage et la coupe progressive et entre la coupe progressive et la coupe au diamètre limite. La coupe progressive à trois étapes avec éclaircie précommerciale 10 ans après la coupe finale a permis un bon contrôle des feuillus et de la pruche et une forte augmentation de l'épinette et du sapin. La coupe de jardinage avec une intervention à tous les cinq ans a entraîné une augmentation de la pruche, de l'épinette et du sapin avec une diminution des espèces feuillues. Si l'objectif premier est la production de matière ligneuse, un aménagement équienne est très fortement conseillé. Nous recommandons la coupe progressive à deux étapes telle qu'appliquée dans cette expérience avec une modification pour améliorer la composition en espèces et la qualité du peuplement. La qualité du peuplement (la proportion du volume du peuplement que représentent les arbres rebuts) et la composition en espèces ont été influencées par les traitements.

[Traduit par la Rédaction]

Introduction

The experiment reported here represents one-half of a century of effort by a number of USDA Forest Service researchers who influenced the experiment in many ways, often by modifying the study plan in response to economic and social changes and natural disturbances. It started as a timber management experiment and evolved into a study of effects on stand dynamics, productivity, resiliency, and biological diversity (for example, Brissette 1996; Gove 1998; Frank 1992; Seymour and Kenefic 1998; Su and Woods 2001). This report covers the first 40 years of the study representing about one-half of a sawtimber rotation for even-aged red spruce stands in northeastern U.S.A. (Meyer 1929).

At the time that this experiment was established, there were thousands of hectares of clear-cut and partially cut stands of mixed northern conifers in northeastern U.S.A. cut primarily for their spruce and fir timber. Westveld (1953) proposed an approach to managing these forests based on ecological principles advocating the selection system as the

Received 11 July 2002. Accepted 2 June 2003. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 22 October 2003.

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 doi: 10.1139/X03-140

preferred option in most spruce–fir stands. Anticipating a movement toward well-managed stands and heavily influenced by Westveld's ideas, this study was designed to provide information on the best silvicultural practices for managing operable and developing stands of mixed northern conifers. Our analysis was based on an experiment established from 1952 to 1957 on the Penobscot Experimental Forest (PEF) in Maine, U.S.A. Replicated treatments include the selection system on 5-, 10-, and 20-year cutting cycles, uniform shelterwood with two- and three-stage overstory removals, unregulated harvesting, and two variations of diameter-limit cutting. The new stand established under three-stage shelterwood was subsequently left untreated or precommercially thinned. The experiment also included an unmanaged natural area.

A common managerial objective is to decrease the hardwood component and increase spruce (Westveld 1953). Spruce is longer lived than balsam fir, has greater resistance to the spruce budworm and decay, and has a higher commercial value. Less frequently, landowners favor balsam fir (Blum et al. 1983; Benzie, et al. 1983). Despite available silvicultural guides (Frank and Bjorkbom 1973), no consensus has been reached about issues such as thinning methods and timing, residual stocking levels, or whether commercial thinning is even desirable (Seymour 1995). Natural regeneration in the region is prolific (Brissette 1996). Principal species are very shade tolerant and regenerate in either partial shade or full sunlight.

Bickford et al. (1961) and Safford (1968) estimated the average volume growth rates in natural extensively managed stands in the spruce–fir region of northern New England based on a sample of approximately 800 plots. The overall estimate of annual net growth after 5 years was 3.2 ± 0.2 $m^3 \cdot ha^{-1}$ and after 10 years was 2.9 ± 0.1 $m^3 \cdot ha^{-1}$. Frank and Blum (1978) examined data for approximately the first 20 years of this experiment for selected treatments. Their objective was to examine the early results of the selection system of silviculture, and they compared stand quality, species composition, diameter distribution, stand density, and growth on selection treatments, unregulated harvest, and unmanaged natural area. At approximately 20 years into the experiment, periodic annual net growth in volume by treatment varied from 4.2 $m^3 \cdot ha^{-1}$ for one of the selection treatments to 0.7 $m^3 \cdot ha^{-1}$ for the unmanaged area. Solomon and Frank (1983) used data from approximately the same time period as Frank and Blum (1978) and estimated growth response related to residual basal area and frequency of harvesting for the selection treatments. Overall, they found an average annual net growth in volume of 3.8 $m^3 \cdot ha^{-1}$. They concluded that there was not a "definite relationship" between net growth and residual basal area for the total stand but that net growth of sawtimber increased with increasing residual basal area, while net growth of poletimber decreased and harvest interval had very little influence on growth response. Deficits in the middle size classes and surpluses of large trees have accumulated in one of the selection treatments (5-year cutting cycle) on the PEF during the last 20 years (Seymour and Kenefic 1998; Kenefic and Seymour 1999). Analysis further indicated that the imbalance was even more dramatic when the age of trees was directly examined instead of size.

This report evaluates volume growth and yield, species composition changes, quality, and to a limited extent, structure of mixed northern conifer stands managed under eight different silvicultural techniques for a period of 40 years. The experiment primarily was designed to study treatments applied to operable stands. However, precommercial thinning was applied to a portion of the new stand resulting from one of the treatments. The main hypothesis tested was that growth and yield was affected by treatment. Changes in species composition and stand quality and structure were examined but not subject to statistical testing.

Materials and methods

Site description

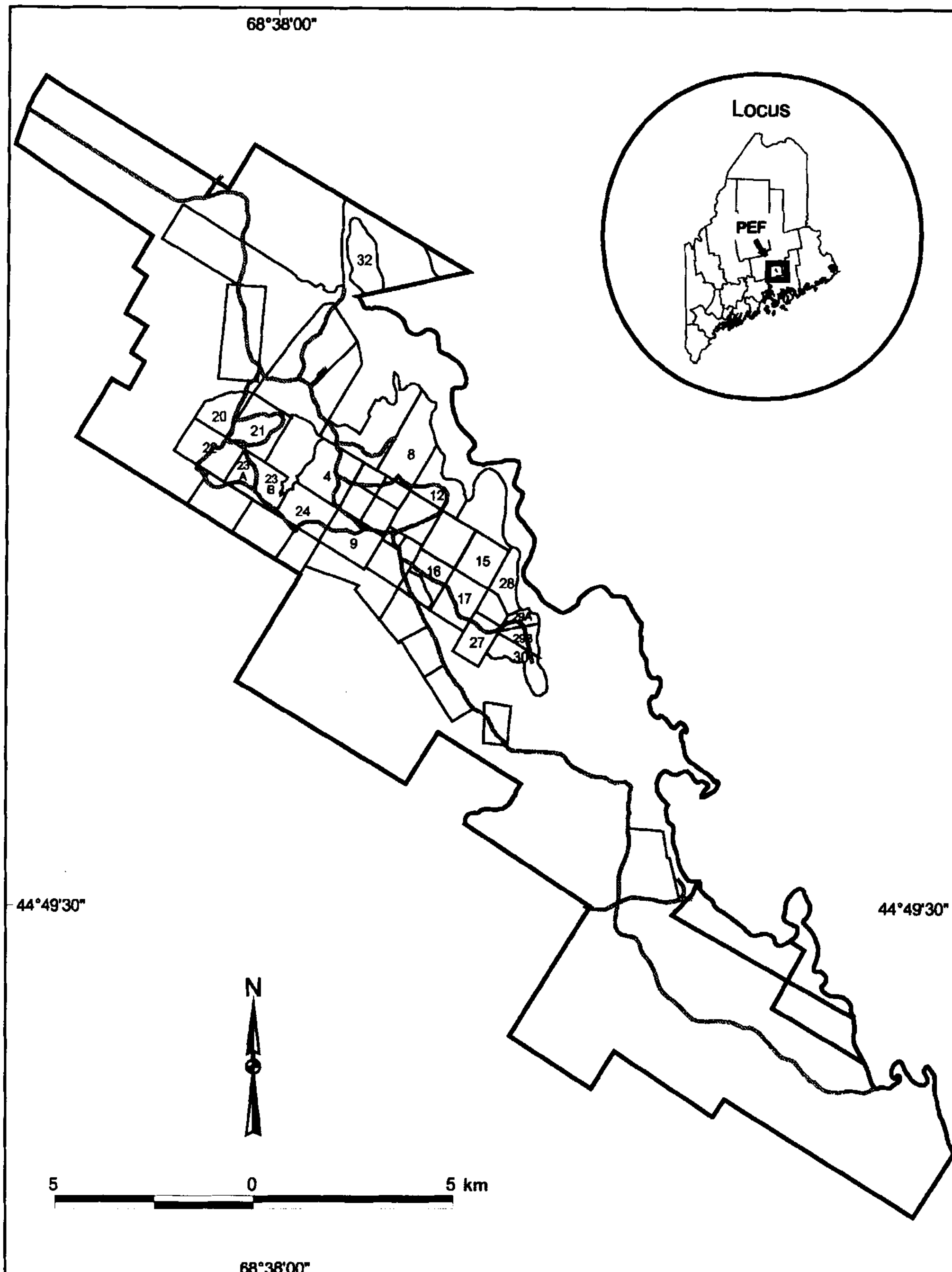
The 1619-ha Penobscot Experimental Forest near Bangor, Maine (Fig. 1), has a cool and humid climate with a 30-year (1951–1980) mean annual temperature at nearby Bangor of 6.6 °C. February had an average daily temperature of −7.0 °C, while July averaged 20.0 °C. Normal annual precipitation is 106 cm, with 48% falling from May through October. Annual snowfall averages 239 cm.

The treatments were installed on approximately 170 ha located in the northern half of the PEF. The PEF is located in the Acadian Forest, an ecotone between the eastern broadleaf and boreal forests. The Acadian Forest includes a mixture of northern conifers and hardwoods dominated by spruces (*Picea* spp.) and balsam fir (*Abies balsamea* (L.) Mill.). Halliday (1937) first described it in a classification of Canada's forests, with the Acadian Forest region spanning the provinces of New Brunswick, Nova Scotia, and Prince Edward Island, and in the U.S., Maine and higher elevations of the Appalachian Mountains.

Mixed northern conifers dominate the PEF, including spruce, mostly red (*Picea rubens* Sarg.) with some white (*Picea glauca* (Moench) Voss); balsam fir; eastern hemlock (*Tsuga canadensis* (L.) Carrière); northern white-cedar (*Thuja occidentalis* L.); eastern white pine (*Pinus strobus* L.); and infrequently, black spruce (*Picea mariana* (Mill.) BSP), tamarack (*Larix laricina* (Du Roi) K. Koch), or red pine (*Pinus resinosa* Ait.). The most common hardwoods are red maple (*Acer rubrum* L.), paper birch (*Betula papyrifera* Marsh.), gray birch (*Betula populifolia* Marsh.), and aspen, both quaking (*Populus tremuloides* Michx.) and bigtooth (*Populus grandidentata* Michx.). Sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), American beech (*Fagus grandifolia* Ehrh.), white ash (*Fraxinus americana* L.), black cherry (*Prunus serotina* Ehrh.), northern red oak (*Quercus rubra* L.), and American basswood (*Tilia americana* L.) occur infrequently on the forest.

The predominant cover types on the research compartments were red spruce – balsam fir and eastern hemlock (Griffin 1980; Wiant 1980). Although typing was difficult because of the mixture of northern conifers, the majority or near majority of the initial stocking was represented by spruce–fir in seven of the research compartments and hemlock in four compartments. Spruce–fir stocking was highest in the most northern compartments (8, 12, 20, 21, 22, 23, and 32), and hemlock stocking was highest in the southern compartments, particularly 15, 16, 17, and 27 (Fig. 1). The

Fig. 1. Location of the Penobscot Experimental Forest in Maine, U.S.A., and location of experimental compartments and roads.



remaining compartments did not have a majority of stocking in any one species or species group, but initial spruce, fir, and hemlock stocking together represented a majority.

The height of the canopy before the treatments were installed was not recorded. However, more recently, total heights have been measured in three of the selection compartments (16, 12, and 20). Based on a sample of 100 dominant and codominant trees, mostly red spruce and eastern hemlock, average height was 18.4 m. The history of the PEF before 1950 is not well documented. In 1950, stands on the PEF appeared uneven aged and were probably irregular, uneven aged in structure as a result of natural stand development confounded by periodic partial cutting. We selected three compartments to examine diameter distribution, a red spruce – balsam fir type (20), an eastern hemlock type (15), and an indeterminate type where spruce, fir, and hemlock together accounted for the majority of stocking (24). The three diameter distributions were similar before treatments were installed and were generally reverse J-shaped, suggesting an uneven-aged structure. In an evaluation of compartment 16 where both diameter at breast height (DBH) and age were measured, balsam fir and hemlock were well represented across the age structure (within the limits of their longevity: fir from 10 to 80 years and hemlock from 10 to 200 years), and red spruce was primarily restricted to two older age cohorts: 90 and 120 years (Kenefic and Seymour 1999; Seymour and Kenefic 1998).

The study area is predominantly spruce–fir flat, characterized by thin, shallow, often wet soils. Briggs (1994) classified spruce–fir sites in Maine based on soil drainage class: site 1, which was well drained and most productive to site 5, which was very poorly drained and least productive. The research compartments were mostly classified as site classes 3–4: somewhat poorly to poorly drained and mediocre in productivity. Soils on the PEF are Wisconsin glacial till derived from fine-grained, dark-colored sedimentary rock. The glacial till ridges are well drained Plaisted loams and stony loams and moderately well-drained Howland loams and sandy loams. Poorly and very poorly drained Monarda and Burnham loams and silt loams occupy flat till areas between the ridges. Outcroppings of vertically bedded shale are covered by a thin mantle of Throndike stony and very stony loams (Safford et al. 1969). The lowest areas along the present watercourses and depressions have moderately well-drained Buxton silt loam, poorly drained Scantic silt loam, and very poorly drained Biddeford silt loam and silty clay loams.

Long-term study

Replicated treatments, established from 1952 to 1957, included the selection system on 5-, 10-, and 20-year cutting cycles, uniform shelterwood with two- and three-stage overstory removals, unregulated harvesting, and two variations of diameter-limit cutting. The new stand established under three-stage shelterwood was subsequently left untreated or precommercially thinned. The experiment also included an unmanaged natural area. In Westveld's (1953) proposal for managing the eastern spruce–fir forest, he stated that mature and overmature even-aged stands could be successfully regenerated to spruce–fir by clear-cutting if sufficient advance regeneration was present or by strip cutting if it was not. But for operable stands that were uneven aged, he proposed the selection system or shelterwood system where selection cutting was financially or otherwise impractical. Unregulated harvesting and diameter-limit cutting were widely practiced methods of exploitive harvesting that focused on the cut rather than residual stand or regeneration. It was the condition of residual stands resulting from these types of cutting that concerned Westveld and others in the 1950s.

Uneven-aged (selection) treatments

Three intensities of single-tree selection silviculture were initially established, but a combination of single-tree and group selection has been used since the mid-1980s. The compartments were managed under the *BDq* method (Guldin 1991), where *B* is residual basal area, *D* is maximum residual DBH, and *q* defines the number of trees in each diameter class. A *q* of 1.4 (2.5-cm diameter class) was applied to all selection stands. Diameter was measured in English units to 0.1 inch and conversion to metric (1 inch = 25.4 mm) does not imply an accuracy of 1 mm. The maximum residual DBH (*D*) was 48.3, 45.7, and 40.6 cm for a 5-year selection (S05), 10-year selection (S10), and 20-year selection (S20), respectively. The residual basal area goal (*B*) was 26.4, 23.0, and 18.4 $m^2 \cdot ha^{-1}$ for S05, S10, and S20, respectively. Species composition goals (% basal area, trees ≥1.3 cm DBH) were as follows: spruce, 35–55; hemlock and fir, each 15–25; and pine, cedar, paper birch, and all others combined, each 5–10.

The 5-year cutting cycle (S05) included cultural treatment of trees down to 2.5 cm DBH and occasionally pruning. Compartment 9 was initially harvested in May 1954 and compartment 16 in March 1957 (Fig. 2). Both had nine entries during the first 40 years of the study. Compartments 12 and 20 were set up in November 1954 and February 1957, respectively (Fig. 2), and had a 10-year operating interval (S10). Both had five entries.

Compartments 17 and 27 (Fig. 2) were established in May 1955 and in May 1957, respectively, using a 20-year operating interval (S20). Each replicate had three entries. In these cases, cultural treatment extended down to 12.7 cm diameter and fewer trees were pruned than in either S05 or S10.

Even-aged treatments

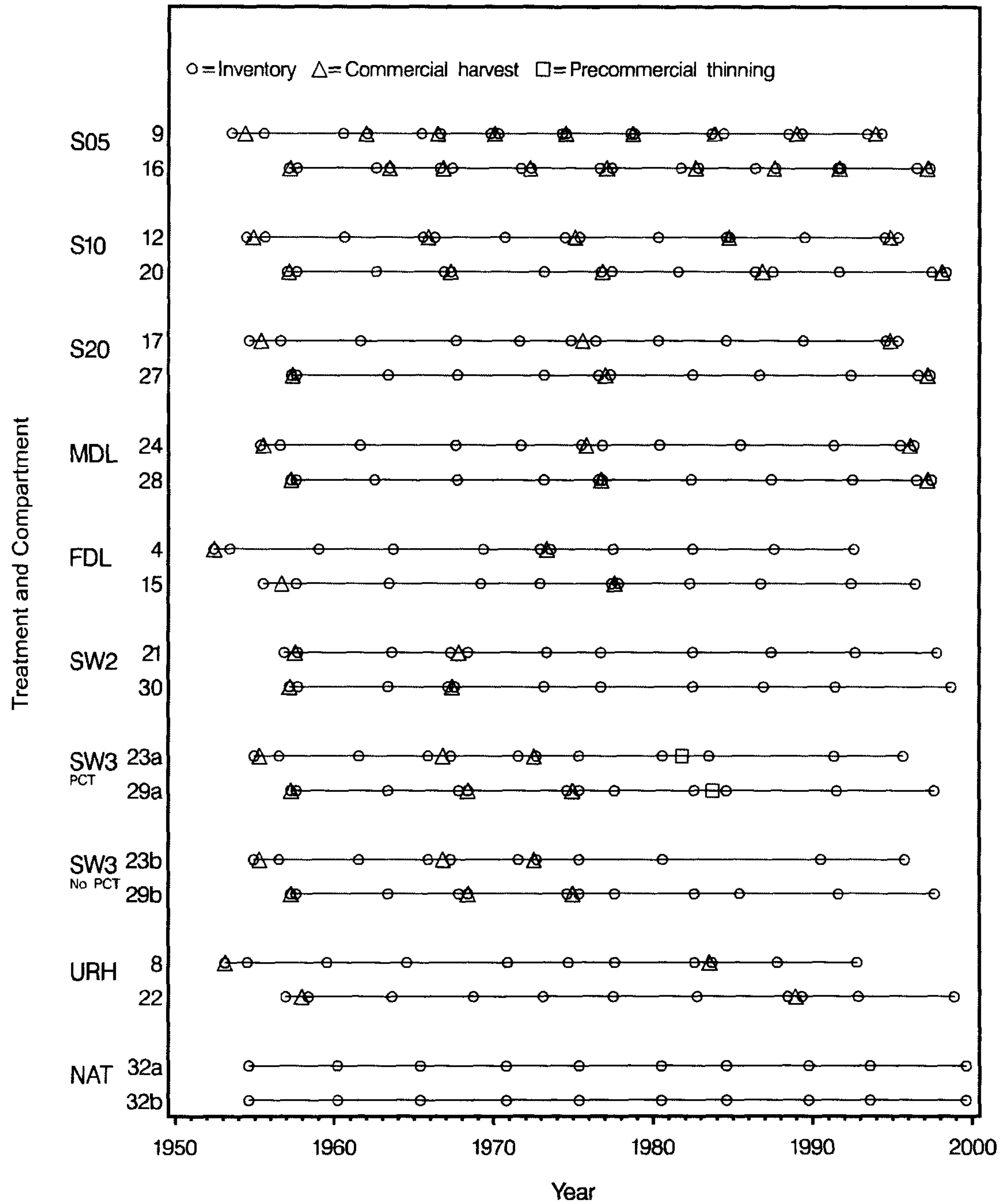
Shelterwood method

The shelterwood treatments initially consisted of two- and three-stage (or cut) shelterwood methods. Because the stands were mature and the desired species well adapted to understory conditions, advance regeneration was present. The uniform two-stage treatment (SW2) was not followed by cultural treatment. The replicates in compartments 21 and 30 were initially cut in November 1956 and March 1957, respectively (Fig. 2). The overstory was finally removed approximately 10 years after the initial cut. Unmerchantable trees, regardless of size, were not removed during the final cut, leaving an approximate basal area of 7 $m^2 \cdot ha^{-1}$ of new cohort and residual trees.

Compartment 23 (set up in April 1955) and compartment 29 (set up in April 1957) were replicates of a three-stage uniform shelterwood method, SW3 (Fig. 2). Three removal cuts were timed to keep shade-intolerant species in check and enhance development of the desired species. The initial cutting removed overmature, defective, or slow-growing trees and less desirable species. This created conditions favorable for the development of existing regeneration, establishment of further regeneration, and increased spacing of growing stock to encourage diameter growth. The second cutting in approximately 10 years removed the poorest trees, stimulated the growth of advance regeneration, and promoted additional reproduction. The third and final cutting after 18 years removed all remaining trees ≥6.4 cm DBH, leaving a basal area of about 0.7 $m^2 \cdot ha^{-1}$ of the new cohort. During early stand entries, silvicides were sometimes used to kill individual cull or unwanted trees. Herbicides were not applied to release the new cohort from competition.

These two compartments were divided to accommodate a precommercial thinning treatment (SW3p) in compartments 23a and 29a in November 1981 and October 1983, respectively (Fig. 2). Workers thinned the new stands manually, clearing 2-m swaths and leaving 1-m strips. Crop trees within these reserved strips were released from competition at approximately 2.4-m intervals, favoring spruce. This left

Fig. 2. Timelines of treatments by compartment showing timing of initiation, inventories, commercial harvests, and precommercial thinnings during the first 40 years of the experiment. S05, 5-year selection; S10, 10-year selection; S20, 20-year selection; MDL, modified diameter limit; FDL, fixed diameter limit; SW2, two-stage shelterwood; SW3, three-stage shelterwood; URH, unregulated harvest; NAT, natural area; PCT, precommercial thinning.



approximately 1668 crop trees·ha^{-1}. The precommercial thinning took place approximately 10 years after final overstory removal.

Diameter-limit cutting

Diameter-limit cutting has often been used in northern conifer stands and was included in the study in two variations. Compartments 4 and 15 were cut to fixed diameter limits (FDL) in June 1952 and September 1956, respectively (Fig. 2). All merchantable trees of desirable species and exceeding the diameter limits were removed (Table 1). Undesirable species, culls, and desirable trees below minimum diameter limits were retained. The second entry occurred when operable volume grew to the initial volume (in approximately 20 years). Possibly because merchantability standards changed, volumes removed in initial and second

Table 1. Diameter limits (centimetres) applied in the fixed diameter-limit (FDL) and modified diameter-limit (MDL) treatments for initial and subsequent cuts by compartment.

	FDL				MDL	
	4		15		24 and 28	
Species	FC	SC	FC	SC	FC	SC
Spruce	24.1	24.1	24.1	24.1	24.1	36.8
Fir	14.0	16.5	16.5	16.5	16.5	16.5
Pine	26.7	29.2	26.7	29.2	26.7	36.8
Hemlock	24.1	24.1	24.1	24.1	24.1	31.8
Tamarack	19.1	29.2	16.5	29.2	—	31.8
Cedar	—	19.1	19.1	19.1	—	19.1
Paper birch	19.1	21.6	19.1	21.6	19.1	24.1
Other hardwoods	14.0	16.5	16.5	16.5	16.5	14.0

Note: Measurements are of the diameter at breast height (DBH). FC, first cut; SC, subsequent cuts; —, data unavailable.

harvests differed in both compartments, and substantially in compartment 4.

Compartments 24 and 28 were treated with modified diameter-limit cutting (MDL) (Fig. 2) in July 1955 and April 1957, respectively. Two additional entries were made every 20 years, removing most merchantable trees above specified diameter limits and harvesting the periodic growth of the previous 20 years. Undesirable species, culls, and most desirable trees below minimum diameter limits were retained (Table 1). Trees above the specified limits were sometimes left as a seed source and for wind protection. High-risk trees of desirable species below the specified limits were taken to avoid their total loss.

Unregulated harvest

In the unregulated harvest treatment (URH), most or all of the commercial value was removed with no plan for regenerating a new stand. The cutting left unmerchantable trees (undesirable species and culls regardless of diameter class) scattered or in small patches. This treatment was applied to compartment 8 in February 1953 and compartment 22 in December 1957 (Fig. 2). After 30 years, there was sufficient volume to repeat the cutting strategy. The second harvest was also a commercial clearcut, but greater volume was removed possibly because merchantability standards changed. No cultural activities were included as part of this program.

Unmanaged or natural area

The study did not have a true replicated control from the beginning. However, compartment 32, first measured in August 1954, has served as an unmanaged check or natural area (NAT) with no harvesting or cultural activities. In 1993, compartment 32 was subdivided into compartments 32a and 32b when we recognized that the two areas had developed different stand structures after sufficient overstory trees died to release the understory of saplings within approximately one-third of the compartment. These two compartments served as the replicated control for purposes of analysis (Fig. 2).

Measurements

A network of 307 systematically located permanent sample points (with a random start) was established. Measurements were taken before and after each cutting treatment and approximately every 5 years following each harvest (Fig. 2). Trees ≥11.4 cm DBH were individually numbered; species DBH and condition were recorded on 0.08-ha circular plots centered on the sample points; and trees ≥1.3 cm DBH were numbered and measured on 0.02-ha circular plots centered within the larger plots. Volume, cull volume, basal area, growth, number of trees, species composition, and diameter distribution were determined using the plot data. Yield was calculated as the difference between pre- and post-cutting inventories. Mortality was recorded at each inventory except postcutting to avoid confusing logging-caused mortality with trees actually harvested. Mortality resulting from harvest operations was recorded at the next inventory.

Harvesting

Each compartment was managed as a unit and commercially logged by independent logging contractors, with stumpage sold either through bid or negotiation. Logging equipment varied over time as technology changed, starting with horse logging and progressing to cut-to-length harvesters with forwarders. Most compartments were harvested using chainsaws and rubber-tired skidders. The compartments were accessed through a system of permanent roads (Fig. 1) and skid trails. Trees to be cut were marked by a USDA Forest Service crew except for URH, which was not marked. The logger, contractor, or Forest Service crew applied cultural treatments.

Growth and yield

Volume growth was the principal concern of the study. Tree volumes were estimated using local volume tables interpolated from standard volume tables (Cary 1932) based on a sample of over 5000 trees ≥11.4 cm DBH on the PEF. Volumes are of solid wood, exclusive of stump, to a 10-cm top by species for 2.5-cm diameter classes. We estimated the merchantable volume for trees ≥11.4 cm DBH (the lower limit of merchantability in the area). Gross volume growth is the volume at the most recent inventory plus mortality during the measurement period plus volume harvested during that period minus the volume at the beginning of the measurement period (Marquis and Beers 1969; Husch et al. 1972). Net growth is gross growth minus mortality. Net growth and gross growth are presented as net or gross periodic annual increment by annualizing the change between the initial and most recent inventory (approximately 40 years).

One-way analysis of variance (ANOVA) was used to test the hypothesis of no difference between treatment means for net volume growth, gross growth, accretion, ingrowth, and mortality. A significant overall F statistic ($\alpha = 0.10$) was followed by a multiple range test (Tukey's HSD) to test for differences between means. The following treatment comparisons for net and gross volume growth were planned as part of the statistical analysis:

(1) Managed vs. unmanaged (S05, S10, S20, FDL, MDL, URH, SW2, SW3p, and SW3 vs. NAT)
(2) Selection vs. shelterwood (S05, S10, and S20 vs. SW2, SW3p, and SW3)

Table 2. Average annual growth in volume (cubic metres per hectare per year) by components and treatment in order of decreasing net growth for trees ≥11.4 cm diameter at breast height (DBH).

Treatment	Accretion[a]	Ingrowth[b]	Gross growth[c]	Mortality[d]	Net growth[e]
S05	3.21ab	0.58ab	3.79ab	0.40	3.40
MDL	3.64a	0.62ab	4.27a	0.99	3.27
FDL	3.12ab	0.73ab	3.85ab	0.80	3.05
S20	3.06ab	0.48ab	3.54ab	0.74	2.79
S10	3.02ab	0.69ab	3.71ab	0.99	2.72
SW2	2.30ab	0.86a	3.16ab	0.63	2.52
SW3p	2.32ab	0.34b	2.66b	0.40	2.25
SW3	2.10b	0.41b	2.51b	0.41	2.09
URH	2.29ab	0.67ab	2.96ab	0.95	2.01
NAT	3.56ab	0.51ab	4.08a	2.49	1.59

Note: Means followed by the same letter within a column are not significantly different by Tukey's HSD method ($\alpha = 0.10$). Means in columns with no letters are not significantly different. S05, 5-year selection; MDL, modified diameter limit; FDL, fixed diameter limit; S20, 20-year selection; S10, 10-year selection; SW2, two-stage shelterwood; SW3p, three-stage shelterwood with precommercial thinning; SW3, three-stage shelterwood; URH, unregulated harvest; NAT, natural area.

[a]Mean square error = 0.196, $F_{[9,10]} = 3.27$. Minimum significant difference = 1.54 m^3.

[b]Mean square error = 0.013, $F_{[9,10]} = 3.89$. Minimum significant difference = 0.39 m^3.

[c]Mean square error = 0.153, $F_{[9,10]} = 4.73$. Minimum significant difference = 1.36 m^3.

[d]Mean square error = 0.331, $F_{[9,10]} = 2.27$.

[e]Mean square error = 0.720, $F_{[9,10]} = 0.95$.

(3) Shelterwood vs. diameter limit (SW2, SW3p, and SW3 vs. FDL and MDL)
(4) Selection vs. diameter limit (S05, S10, and S20 vs. FDL and MDL)
(5) Two-stage shelterwood vs. three-stage shelterwood (SW2 vs. SW3p and SW3)

Results

The ANOVA of net volume growth indicated no significant difference between treatment means (Table 2). Gross volume growth for the MDL and NAT treatments was significantly greater than that for the SW3p and SW3 treatments. Pairwise comparisons between similar treatments (i.e., the two diameter limits, three selection treatments, and three shelterwood treatments) showed no significant differences between treatment means.

For accretion in volume, there was a significant difference between the two extreme treatments: MDL with the greatest accretion and SW3 with the least (Table 2). For ingrowth (trees ≥11.4 cm DBH), there was a significant difference between SW2 with the greatest ingrowth and SW3p and SW3 with the least. For mortality, there were no significant differences between treatment means.

None of the treatment comparisons for net volume growth were significant ($\alpha = 0.10$) and are not presented here. For gross volume growth, the difference between management and no management was significant (Table 3). Application of some type of harvest cutting resulted in less gross volume growth than that for not cutting. Selection treatments resulted in significantly more gross volume growth than that for shelterwood treatments. Shelterwood treatments resulted in less gross volume growth than that for diameter-limit treatments. The differences in gross volume growth between (*i*) selection treatments and diameter-limit treatments and (*ii*) two-stage shelterwood and three-stage shelterwood were not significant.

Differences between treatment yields from the harvested compartments were not significant ($\alpha = 0.10$). Overall mean harvested volume for the study was 171.7 $m^3 \cdot ha^{-1}$, which does not include the zero harvest in NAT. Timing of harvests and volume cut vary by treatment, with two cuts in UHR, SW2, and FDL (Table 4) and nine cuts in S05 (Table 5).

Diameter distributions

Diameter distributions prior to treatment and at 40 years were plotted for three representative compartments: 15, an eastern hemlock type (FDL); 20, a red spruce – balsam fir type (S10); and 24, where spruce, fir, and hemlock together accounted for a majority of the stocking (MDL) (Fig. 3). Initially, the diameter distributions of all three compartments were similar. An uneven-aged distribution with balanced size classes would be a straight line on a log scale, such as used in Fig. 3. At the start of the experiment, these compartments all showed deviations from a straight line, indicating deficits and surpluses in some diameter classes. Compartment 15 was approaching a third cut under FDL at 40 years. The diameter distribution at 40 years was similar in shape to the initial distribution, but there were more small trees (<15 cm) at 40 years and fewer trees >15 cm, with a few large (probably cull) trees left from earlier cuts. Volume was slightly more than half the initial volume and percentage of volume in cull trees had doubled at 40 years from 6.8% to 14.2%.

Compartment 20, managed under S10, at 40 years was just postharvest for the fifth cut. Diameter classes for smaller trees, 12–16 cm, were in deficit compared with the treatment target, but there was a surplus for larger trees, 28–46 cm (Fig. 3). There were also trees larger than the 46-cm target maximum diameter. Percentage of volume in cull trees had decreased at 40 years from 6.5% initially to 1.2%.

Table 3. Planned comparisons, gross volume growth (trees ≥11.4 cm DBH).

Comparison	Difference ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	F value	$P > F$
Management vs. no management	–0.70 (±0.53)	5.72	0.038
Selection vs. shelterwood	0.91 (±0.41)	16.03	0.003
Shelterwood vs. diameter limit	–1.29 (±0.46)	25.84	0.001
Selection vs. diameter limit	–0.38 (±0.46)	2.26	0.164
Two- vs. three-stage shelterwood	0.58 (±0.62)	2.86	0.122

Note: Values in parentheses represent the 10% confidence limit. Degrees of freedom for F are 1 and 10.

Table 4. Harvested volumes (cubic metres per hectare) by treatment and harvest for even-aged and diameter-limit treatments.

	Treatment				
Harvest No.	URH	SW2	SW3[a]	FDL	MDL
1	73.6	67.3	47.4	70.3	42.4
2	123.1	108.7	86.9	95.6	77.9
3	—	—	58.2	—	50.0
Total	196.7	176.0	192.5	165.9	170.3

Note: For relative date of harvest, see Fig. 2. URH, unregulated harvest; SW2, two-stage shelterwood; SW3, three-stage shelterwood; FDL, fixed diameter limit; MDL, modified diameter limit; —, not applicable.
[a]SW3p had a precommercial harvest in which an additional 1.7 $m^3 \cdot ha^{-1}$ was harvested.

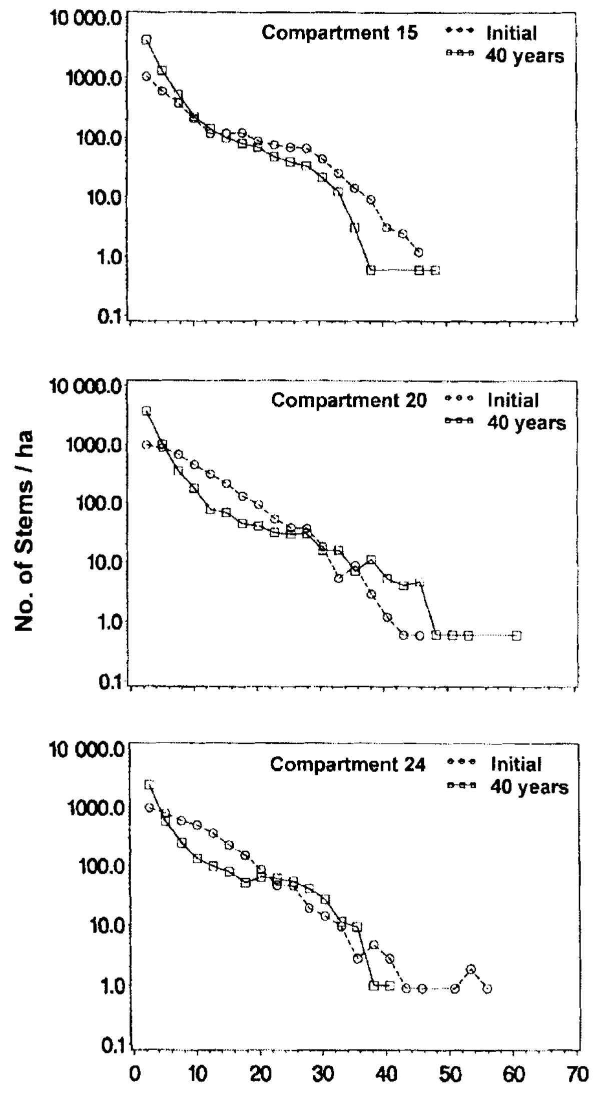
Table 5. Harvested volumes (cubic metres per hectare) by treatment and harvest for selection treatments.

	Treatment		
Harvest No.	S05	S10	S20
1	29.1	45.4	39.1
2	15.0	28.2	99.7
3	12.9	29.3	37.5
4	15.1	17.3	—
5	11.6	15.8	—
6	11.4	—	—
7	14.6	—	—
8	14.6	—	—
9	13.3	—	—
Total	137.6	136.0	176.3

Note: For relative date of harvest, see Fig. 2. S05, 5-year selection; S10, 10-year selection; S20, 20-year selection; —, not applicable.

Compartment 24, managed under MDL, at 40 years was just postharvest for the third cut. There were fewer small trees (5–18 cm) at 40 years and more trees from 28 to 32 cm, with a few trees >36 cm, the largest diameter limit applied in this stand (Fig. 3). Percentage of volume in cull trees had changed little at 40 years from 6.9% to 7.5%.

Fig. 3. Diameter distributions at initial and 40-year inventories for three compartments: 15, eastern hemlock type (FDL); 20, red spruce – balsam fir type (S10); and 24, where spruce, fir, and hemlock together accounted for a majority of the stocking (MDL).



Basal area growth trajectories

The trajectories of basal area through time for live trees of 1.3 cm DBH are shown by treatment in Fig. 4. A reference line at 33.4 $m^2 \cdot ha^{-1}$ was the average basal area for all the compartments at the initial inventory prior to treatment. The trajectories show the timing and amounts harvested by treatment for the 40-year period. The extremes were NAT with no cutting and S05, with a harvest approximately every 5 years. The remaining treatments have had two or three entries, with the exception of SW3p (four entries) and S10 (five entries). The impact of the last spruce budworm out-

Fig. 4. Trajectories of basal area growth by treatment for live trees ≥1.3 cm diameter at breast height (DBH). Horizontal lines represent initial basal area averaged over all compartments (33.4 $m^2 \cdot ha^{-1}$). URH, unregulated harvest; SW2, two-stage shelterwood; SW3, three-stage shelterwood; FDL, fixed diameter limit; NAT, natural area; MDL, modified diameter limit; S05, 5-year selection; S10, 10-year selection; S20, 20-year selection.

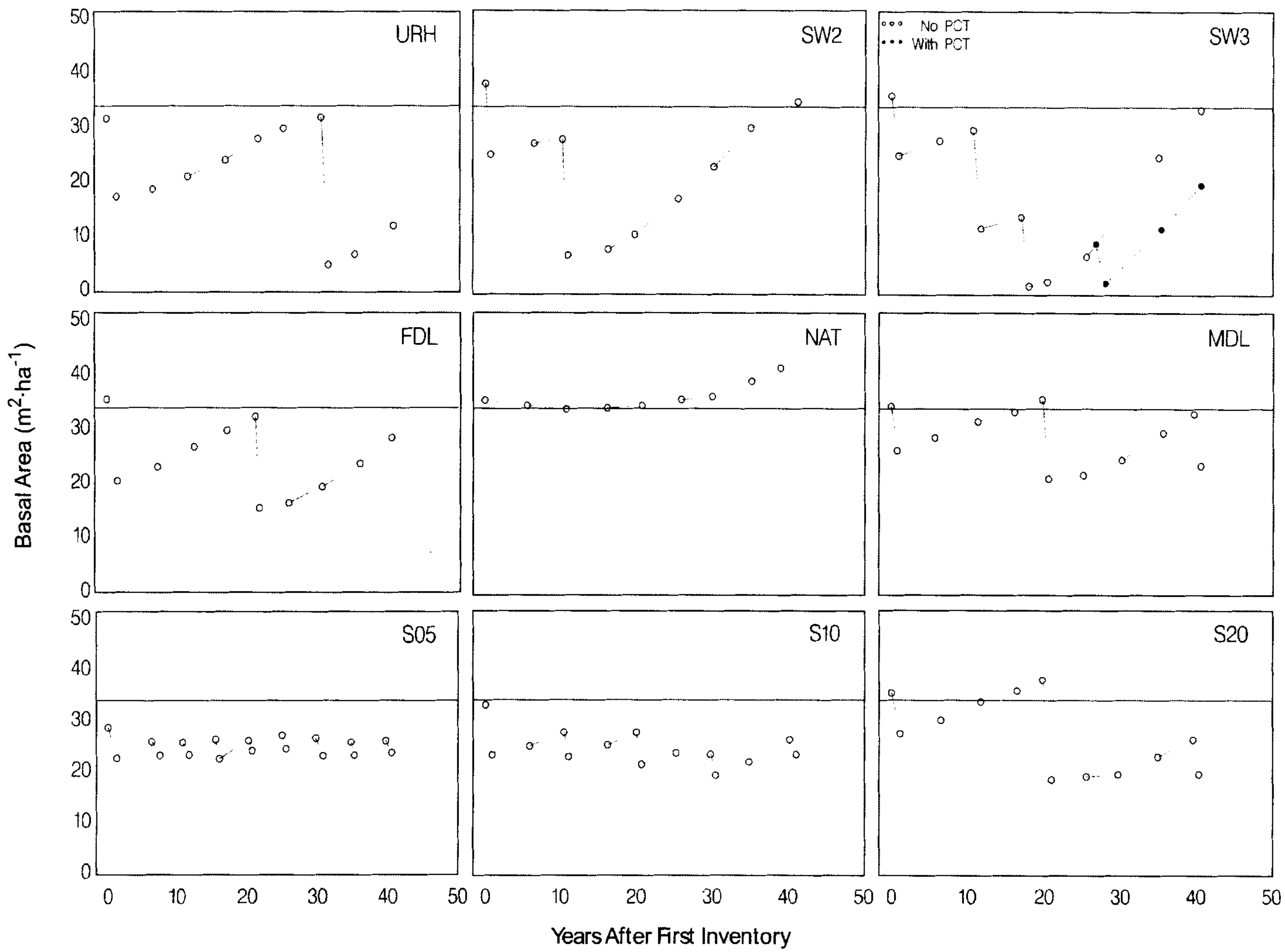


Table 6. Species composition by treatment at time of first inventory and 40-year inventory expressed as a percentage (%) of total basal area (square metres per hectare) for all live trees ≥1.3 cm diameter at breast height (DBH).

		Species						
Treatment	Inventory	Spruce	Fir	Hemlock	Pine	Other softwoods	Hardwoods	Total basal area
URH	Initial	15	29	19	4	12	21	31.0
	40 years	5	30	3	2	9	51	11.5
SW2	Initial	18	25	22	5	12	18	37.6
	40 years	11	41	11	3	9	25	34.3
SW3	Initial	18	21	30	9	6	16	34.4
	40 years	24	43	4	14	<1	15	32.9
SW3p	Initial	18	21	30	9	6	16	34.4
	40 years	40	37	4	2	<1	17	19.2
S05	Initial	14	11	37	3	13	22	28.1
	40 years	23	14	41	7	4	11	23.2
S10	Initial	21	35	17	2	10	15	32.4
	40 years	36	21	18	2	7	16	22.7
S20	Initial	15	15	47	2	15	6	34.8
	40 years	30	14	36	1	7	12	18.9
FDL	Initial	18	12	33	2	21	14	33.2
	40 years	12	23	31	2	8	24	27.8
MDL	Initial	19	28	25	4	7	17	33.8
	40 years	29	13	33	2	7	16	23.0
NAT	Initial	12	32	17	20	6	13	34.9
	40 years	10	16	25	23	4	22	40.7

Note: URH, unregulated harvest; SW2, two-stage shelterwood; SW3, three-stage shelterwood; SW3p, three-stage shelterwood with precommercial thinning; S05, 5-year selection; S10, 10-year selection; S20, 20-year selection; FDL, fixed diameter limit; MDL, modified diameter limit; NAT, natural area.

break was evident in the treatments with more mature trees, particularly the selection treatments and NAT.

Species composition response

The overall goals in managing stands of northern conifers on the PEF were to increase the softwood component and to increase the spruce component relative to balsam fir. Of the three other conifers that commonly occur with spruce and fir, white pine is the most valuable and was favored as a crop tree over hemlock and northern white-cedar.

In reference to the goal of increasing the softwood component, treatments were evaluated based on the change in the hardwood component as measured by the percentage of basal area in hardwood species in the initial inventory compared with the percentage of basal area in the 40-year inventory (live trees ≥1.3 cm DBH). Only treatment S05 has been successful in reducing the hardwood component substantially (from 22% to 11% of the basal area) (Table 6). For several treatments, the hardwood component has remained approximately the same (within 1 percentage point): SW3, MDL, SW3p, S10. The remaining four treatments all had substantial increases in the hardwood component, with the greatest increase in URH (from 21% initially to 51% in the 40-year inventory). NAT, which had no harvesting activity, also increased in hardwoods from 13% initially to 22% over the 40-year period.

Spruce increased as a percentage of basal area over the 40-year period in S05, S10, S20, MDL, SW3, and SW3p (Table 6). The spruce component decreased in URH, SW2, FDL, and NAT. The greatest relative increase occurred in SW3p, where basal area increased from 18% initially to 40% in year 40. The lowest percentage of spruce at year 40 occurred in URH (5%).

The balsam fir component increased substantially in SW2, SW3, SW3p, and FDL; increased slightly or remained about the same in S05, S20, and URH; and decreased in S10, MDL, and NAT (Table 6). Where the silvicultural system has included treatments that favor spruce over fir, i.e., in SW3p but not SW3, a dramatic increase in spruce resulted (Table 6). In S05, S10, and S20, spruce increased relative to balsam fir over the 40-year period.

The percentage of basal area in hemlock varied widely in the initial inventory from a low of 17% in NAT to a high of 47% in S20 (Table 6). The change in percentage of basal area in hemlock decreased in the SW3, SW3p, URH, SW2, S20, and FDL treatments; increased in the S05, MDL, and NAT treatments; and was unchanged in the S10 treatment. The selection treatments have a goal of reducing the hemlock component to 15%–25% of the basal area (only S10 had met that goal, but S10 met the goal prior to management). S20 started with a large proportion of its basal area in hemlock (47%) and, in 40 years, decreased the percentage of hemlock to 36%. S05 also started with a large proportion of hemlock (37%), but the percentage of hemlock increased to 41%.

Stand quality

Volume in cull trees was used as a measure of stand quality. A tree less than half sound volume was considered cull.

Table 7. Cull tree volume by treatment at time of initial and 40-year inventories expressed as percentage of total volume for all live trees ≥11.4 cm diameter at breast height (DBH).

	Inventory			
	Initial		40 years	
Treatment	Cull (%)	Total volume ($m^3 \cdot ha^{-1}$)	Cull (%)	Total volume ($m^3 \cdot ha^{-1}$)
URH	9.2	131.1	21.7	16.1
MDL	8.0	146.7	12.0	105.6
S10	7.4	132.0	1.1	107.9
FDL	7.3	146.7	13.4	104.2
SW2	6.4	159.4	9.8	84.3
S20	6.3	151.4	1.1	87.9
S05	5.0	128.2	0.4	128.3
SW3	4.7	146.6	5.8	39.0
SW3p	4.7	146.6	0.7	43.6
NAT	3.9	162.9	7.3	224.9

Note: URH, unregulated harvest; MDL, modified diameter limit; S10, 10-year selection; FDL, fixed diameter limit; SW2, two-stage shelterwood; S20, 20-year selection; S05, 5-year selection; SW3, three-stage shelterwood; SW3p, three-stage shelterwood with precommercial thinning; NAT, natural area.

In the initial inventory, all treatments had an average cull volume <10% of total volume, ranging from 9.2% for URH to 3.9% for NAT (Table 7). By year 40, URH had the highest percentage in cull volume, 21.7%, and S05 the lowest, 0.4%. Treatments that included timber stand improvement (TSI), selection, and SW3p had a decrease in percentage of cull volume. SW3 also included TSI but had a slight increase in percentage of cull volume. Those treatments that did not remove cull trees had an increase in percentage of cull volume.

Discussion

Average annual net growth in volume on the PEF based on 40-year data was $2.6 \pm 0.2\ m^3 \cdot ha^{-1}$. ANOVA indicated no significant differences between treatment means for annual net growth in volume on the PEF (Table 2). Although the results indicated that the average of all treatments on the PEF was statistically the same as what might be expected regionally, it was anticipated that more intensive management as applied to some compartments on the PEF would increase net growth in volume over regional averages of extensively managed stands, as reported by Safford (1968). For the first 40 years of the experiment, harvests have been of trees that were there before 1950. In most treatments, they have been removed in two or three cuttings but for some, like S10 and S05, removals were extended through several cuttings during the period. The next few cycles of cuts (in 5–20 years) in most treatments will probably be the first to harvest trees that regenerated during the experiment. Future comparisons of net growth may show that some treatments will achieve greater net growth in volume. This is especially true with the even-aged treatments in which ingrowth and accretion will accelerate over the next few years. However, based on the data collected for the first 40-year period, there are no significant differences between treatment means for annual net growth.

Gross volume growth was significantly different between groups of treatments, indicating differences in mortality. The significant difference in gross growth between management and no management implied that NAT had greater mortality volume than the mean mortality of all the other treatments (Table 3). This was expected because no mortality was captured through harvesting in NAT. Selection treatments as a group and the diameter-limit treatments had significantly more mortality than shelterwood treatments as a group. For most of the 40-year period, the shelterwood stands were regenerating and although suppression mortality was occurring in the new cohort, the trees were smaller than 11.4 cm DBH, and thus not included in the analysis. The differences in gross volume growth between (*i*) selection treatments and diameter-limit treatments and (*ii*) two-stage shelterwood and three-stage shelterwood were not significant, implying no differences in mortality.

Although species composition goals for this study were specified only for the selection treatments, accepted management goals for stands within these forest types include decreasing hardwoods and increasing spruce (Westveld 1953). Only treatment S05 has reduced the hardwood component substantially (Table 6). Harvesting in this treatment resulted in the smallest openings and, consequently, the most shaded understory, a condition unfavorable for hardwoods most common on the PEF. Four treatments (S20, SW2, FDL, URH, and NAT) had a greater hardwood component after 40 years. The treatments were those with the greatest disturbance to the overstory and thus the most light to the forest floor. Part of NAT suffered substantial mortality, which also opened up the canopy. Among the other treatments (SW3, MDL, SW3p, and S10), the hardwood component has remained approximately the same. Canopy openings tended to be moderate in size in S10 and MDL, while in SW3 and SW3p, the high density of regenerating conifers effectively competed with the typically faster-growing hardwoods.

Spruce increased over the 40-year period in S05, S10, S20, MDL, SW3, and SW3p (Table 6). In the selection treatments, species composition goals favor spruce, so it was retained in all diameter classes to a greater extent than other species, even when inferior in form or quality. To a lesser extent that is true in MDL, where spruce larger than the recommended diameter limit could be retained as a seed source. The longer period of a sheltering overstory in SW3 compared with SW2 may have slowed development of balsam fir and allowed spruce to become well established in the regenerating cohort. As in SW2, the open conditions following harvests in FDL and URH resulted in a decrease in the spruce component compared with the initial stand. The greatest relative increase occurred in SW3p, where basal area increased from 18% initially to 40% in year 40. The lowest percentage of spruce at year 40 occurred in URH (5%). Where the treatment has favored spruce over fir, i.e., in SW3p but not SW3, a dramatic increase in spruce resulted. In S05, S10, and S20, spruce increased relative to balsam fir over the 40-year period, largely because the shorter-lived fir was selected for harvest to prevent its loss to mortality.

Hemlock should be of greater concern than hardwoods on this site class. Hemlock sawlogs and pulpwood are worth about half or less of what spruce is worth. Hemlock stocking was great enough in several stands to be classed as the eastern hemlock type. S20, S05, SW2, SW3, and FDL treatments included stands with high stocking of hemlock. In SW3, SW3p, and SW2 treatments, the percentage of basal area in hemlock decreased substantially, but only slightly in S20 and FDL, and increased in S05. Since S05 is one of the most intensive treatments applied in this study and thus one of the most costly, its application in stands with a high proportion of hemlock stocking should be questioned if the primary goal is financial return.

Stand quality, as measured by percentage of volume in cull trees, was also influenced by treatment. The selection treatments SW3 and SW3p removed undesirable trees as part of the stand prescription. All other treatments left undesirable trees to grow as part of the residual stand. Those treatments that did not remove undesirable trees had an increase in percentage of volume in cull trees over the 40-year period. With one exception, those treatments that removed undesirable trees had a decrease in percentage of volume in cull trees. The exception was SW3, which had a slight increase in percentage of volume in cull trees.

The application of the selection system to an uneven-aged stand in an effort to make it a sustained-yield unit requires that diameter classes be adjusted by cutting to make the stand conform to a reverse J-shaped diameter distribution (Smith et al. 1997). The process assumes a strong positive association between tree age and diameter. Deficits in the middle size classes and a surplus of large trees has accumulated in the two compartments in S05 on the PEF during the last 20 years (Seymour and Kenefic 1998; Kenefic and Seymour 1999). Analysis further indicated that the imbalance was even more dramatic when age of trees was directly examined instead of size. Complexities caused by the mixed-species nature of the stands and the extreme shade tolerance of the major species in the stand call into question the sustainability of the uneven-aged management strategy being applied in S05.

The most intensive even-aged treatment in the experiment was three-stage shelterwood with precommercial thinning (SW3p). The results indicate good control of hardwoods without herbicides (17% of basal area), excellent control of hemlock (4% of basal area), and a dramatic increase in spruce (40% of basal area) and balsam fir (37% of basal area).

The most intensive uneven-aged treatment was selection on a 5-year operating cycle (S05). The treatment goal of cutting to a residual basal area of 26.4 $m^2 \cdot ha^{-1}$ has always been exceeded in practice. The hemlock component has increased slightly from an initially high level of 37% of the basal area to 41%. However, the hardwood component has been substantially reduced from an initial 22% of basal area to 11%. Both the spruce and balsam fir components have increased, with spruce increasing more than fir but neither reaching their goal of 35% to 55% spruce and 15% to 25% fir. However, this treatment has developed deficiencies in the pole and small sawtimber classes and thus may not be sustainable under the existing goals, especially residual basal area and steep q (Seymour and Kenefic 1998; Kenefic and Seymour 1999).

Costs to apply and maintain the various treatments and expected harvesting revenues will determine to a large extent what treatments might be applied by managers of similar stands. Although no financial analyses have been done for these treatments, some generalities regarding costs and revenues can be made. The more intensive treatments, such as S05 and SW3p, are expensive to apply. An inventory, an analysis of the diameter distribution (in S05), marking trees to cut, prescribed TSI, precommercial thinning in SW3p, and greater logging costs all contribute to greater costs for these treatments compared with others. However, all the compartments on the PEF are inventoried more frequently than would be done in a production setting because they are part of a controlled experiment. For the same reason, trees were marked for harvest in all the treatments except URH and the final overstory removals in the shelterwood treatments. Rules for selecting trees for harvest could be conveyed to loggers for many of the treatments, avoiding some marking cost. The revenue side also must be considered; greater revenue may offset greater cost. To date, differences in growth and yield between treatments have not been significant. That will likely change as the experiment proceeds and the young even-aged stands begin to accumulate volume. There have been some positive results for changes in species composition and stand quality but probably not to the extent needed to offset the costs. Diameter-limit cutting has a potential cumulative depleting effect on stands by always cutting the larger and higher-quality dominant trees and leaving poorer-formed, slow-growing individuals and culls as seed source in the residual stand (Kenefic et al. 2002). However, given no negative impacts on growth thus far and the low cost of applying this treatment, it is important to continue to see how it compares with the other treatments over a longer time frame, at least equivalent to an even-aged rotation.

After 40 years, the experiment represents about half a sawtimber rotation for an even-aged stand in the Acadian Forest. As the even-aged stands regenerated in the unregulated harvest and shelterwood treatments begin to mature, questions about commercial thinning strategies need to be answered. Should commercial thinning be applied, and if so, to which treatments, at what intensity (residual basal area), and which trees should be removed? Are specified *BDq* goals in the uneven-aged stands regenerated under the selection treatments still appropriate or do they need to be revised? What is the best way to control hemlock reproduction, particularly in S05, to decrease the proportion of hemlock?

If production were the primary goal of management, some form of even-aged management would most likely be preferred. A recommendation, based on analysis of the treatments in this experiment so far, would be two-stage shelterwood as applied on the PEF, but with the addition of removing all remaining trees >5–6 cm DBH during the final overstory harvest to eliminate competition from overtopping residual trees. Precommercial thinning should also be considered as the new stand develops, depending on density and species composition objectives. The treatment should result in good to excellent control of species composition and percentage of cull volume, which would have a positive effect on revenue. The cost to apply this treatment would be moderate compared with the other treatments. If favoring spruce over fir was an important management objective, removing the overstory in more than two cuts, and thereby releasing the new cohort more slowly, may be worthwhile.

Acknowledgements

To maintain an experiment of this scale over such a long time requires the dedication and enthusiasm of many people. Tom McLintock conceived the experiment, planned, and established it. Arthur Hart worked with McLintock and then ensured that the study progressed as planned until his death in 1969. Orman Carroll spent over 20 years on the PEF as lead forestry technician overseeing periodic inventories and harvests. Tom Skratt followed Carroll as lead technician. Dick Hosmer and later Tim Stone computerized the records and kept the database current. We are indebted to Laura Kenefic, Bill Leak, Robert Seymour, and Edwin Swift for helpful comments on an earlier draft of this paper and to Tom Luther for creating Fig. 1. Finally, we are indebted to two anonymous Journal referees and especially an Associate Editor for numerous, helpful suggestions for revisions of earlier drafts.

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