Comparison of Fixed Diameter-Limit and Selection Cutting in Northern Conifers

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ABSTRACT: *Diameter-limit cutting is a common type of harvest in which all merchantable trees above specific size thresholds are removed. Despite a long history of application, controlled experiments of these harvests are rare and the cumulative effects of repeated diameter-limit cuts are largely unknown. The Penobscot Experimental Forest in Maine is the location of a long-term USDA Forest Service experiment in which both fixed diameter-limit and selection cutting have been applied at 20-year intervals since the early 1950s. After three entries, present value of gross harvest revenue was greater in the fixed diameter-limit than selection treatments. However, sawtimber volume and growth, total and merchantable volume, regeneration stem density, and inventory value all were lower in the fixed diameter-limit than selection stands. Accumulated value (harvest plus residual) and species composition did not differ between treatments. Within-treatment analysis revealed desirable directional changes in cull percentage and species composition in the selection but not diameter-limit cut stands, suggesting trends that may result in greater future treatment disparity. These data confirm the degrading effects of fixed diameter-limit relative to selection cutting, and reveal that greater short-term value removals are offset by lower residual stand volume and value. North. J. Appl. For. 22(2):77–84.*

Key Words: Diameter-limit cutting, high grading, selection cutting, uneven-aged silviculture, northern conifers.

The forests of northeastern North America have long been subjected to repeated preferential harvests of large trees and high value species (Nyland 1992, Seymour 1995). The impact of this practice was rarely benign and has created a landscape often dominated by smaller and less valuable trees than that of even a century ago. Despite this well-documented large-scale trend in the forest condition, the effects of removal-driven harvests have been little studied at the stand level.

Diameter-limit cutting is a common practice in which only merchantable trees above stand- or species-specific size thresholds are cut. Because diameter-limit cutting is a partial cutting (i.e., only some of the trees are removed from a stand), it often is confused with the selection method: the regeneration method used in uneven-aged silviculture. Silviculture, however, is defined as "controlling the establishment, growth, composition, health, and quality of forests and woodlands" (Helms 1998). Selection cutting, for example, is the simultaneous removal of mature trees, tending of immature classes, and regeneration of a new age class for the purpose of creating and maintaining an uneven-aged stand of high value trees to be periodically harvested over the long-term. The focus of such a treatment is residual stand condition, rather than the quality or quantity of wood removed. Because diameter-limit cutting is removal driven, it is applied without regard for residual stand regeneration, growth, composition, quality, or health.

Nyland (2005) modeled the effects of diameter-limit and selection cutting on long-term sawtimber yields and values in uneven-aged northern hardwood stands. He found that diameter-limit cutting (12-in. diameter limit) resulted in greater sawtimber harvest volume and net present value than selection cutting, but also less regular and less frequent yields of volume and value. Additionally, Nyland found that the advantages of diameter-limit were diminished when the first, heavy cut was not considered. This is consistent with

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Hutnik (1958), who suggested that the benefits of diameter-limit cutting are limited to the initial harvest due to reduced residual stand vigor, quality, and value.

In addition to the effects of cutting on growth and yield, it has been speculated that repeated diameter-limit cuts create unbalanced or unsustainable stand structures, resulting in irregular, long harvest intervals (Blum and Filip 1963). Roach (1974) suggested that heavy cutting of large-diameter northern hardwood trees with little to no tending in the smaller size classes, as is the case in diameter-limit cutting, creates a mid-size class glut of trees that prevents the adequate and timely establishment and release of regeneration, ultimately reducing harvests to low levels after three entries and/or lengthening the harvest interval. Though supported by theory, there are no published reports of cutting trials in which Roach's (1974) idea is evaluated.

Uneven-aged silvicultural treatments are applied with the objective of creating a specific residual diameter distribution and relative density, under the assumption that maintenance of this state will allow periodic and consistent volume removals. This is supported by research in northern hardwoods in New York and the Lake States, in which target diameter distributions were repeatedly recreated in cutting trials or computer simulations, and growth rates remained high (Eyre and Zillgitt 1953, Hansen and Nyland 1987, Nyland 2002).

The objective of the research reported here is to quantify the short- and long-term impacts of diameter-limit and selection cutting in northern conifers. We hypothesize that diameter-limit cutting degrades stand condition, as expressed in species composition, structural sustainability, quality, and value and this degradation makes diameter-limit harvesting ecologically and financially undesirable.

Study Area

The stands sampled in this study are part of a long-term silvicultural experiment on the 4000-ac Penobscot Experimental Forest (PEF) in east-central Maine, located at approximately 44°52′ N, 68°38′ W. The PEF is in the Acadian Forest; an ecotone between the eastern broadleaf and boreal forests. Species composition is dominated by eastern hemlock (*Tsuga canadensis* (L.) Carr.), balsam fir (*Abies balsamea* (L.) Mill.), and spruce (*Picea* species) in mixture with other softwoods and hardwoods such as red maple (*Acer rubrum* L.), and birch (*Betula*) and aspen (*Populus*) species. Research began on the PEF in 1950 when the USDA Forest Service initiated an experiment to study even- and uneven-aged silvicultural systems and exploitive cutting. Treatments and remeasurements have continued to the present and follow a long-term study plan that ensures consistency in management through time. The four stands used for the research reported here are two replicates each of fixed diameter-limit (DL) and selection (SC) cutting on a 20-year cycle.

The fixed diameter-limit treatment (stands C4 and C15) has been applied three times, at years 0, 20, and 40–45 of the experiment (there is a 5-year time lag between replicate treatments for the third cut). All merchantable trees above species-specific diameter limits have been removed at each entry. Size thresholds for removal are 11 in. for eastern white pine (*Pinus strobus* L.), 9 in. for spruce and eastern hemlock, and 8 in. for paper birch (*Betula papyrifera* Marsh.) and northern white-cedar (*Thuja occidentalis* L.). All merchantable trees of other species are removed. Over the first 45 years of the experiment, the diameter limits varied ± 1.0 in. from the above diameters, and the minimum merchantability threshold was lowered from 6.5 in. dbh in the first cut (year 0) to 4.5 in. dbh in the third cut (year 40–45). The study plan specifies that stands are to be re-entered when the volume available for harvest, i.e., merchantable volume above the species-specific diameter limits, equals that removed in the initial entry. The fact that this occurred on or close to 20-year intervals is coincidental, but facilitates comparison with the 20-year selection.

The selection treatment utilizes a structural goal defined using the BD*q* method (Marquis 1978, Guldin 1991), with a *q*-factor of 1.4 on 1-in. dbh classes (1.96 on 2-in. dbh classes), a residual maximum diameter (MaxD) goal of 16 in. dbh, and a target residual basal area (BA for all trees ≥ 0.5 in. dbh) of 80 ft^2/ac. The cutting cycle is 20 years, and treatments have been applied in years 0, 20, and 40 of the experiment. Marking guidelines are used to prioritize removals so that residual stand quality, growth, and species composition are improved. Priorities for removal are as follows:

1. Remove cull trees (>50% unmerchantable by volume).
2. Remove high risk trees (expected to die before the next entry).
3. Release potential crop trees on three sides.
4. Create or enlarge regeneration openings.
5. Remove trees larger than MaxD.

Species composition goals, expressed as a percentage of residual stand BA, are used to further prioritize removals. These goals are as follows: spruce, 35–55%; balsam fir and eastern hemlock, 15–25% each; eastern white pine, paper birch, northern white-cedar, and other, 5–10% each. In practice, efforts to improve species composition, quality, and growth were given priority over strict adherence to the structural goal (Seymour and Kenefic 1998).

Methods

Nested 1/5- and 1/20-ac plots were established on a systematic grid with a random start in year 0 of the experiment. Data have been collected on these permanent fixed-radius plots before and after every harvest and at about 5-year intervals between harvests. Trees ≥0.5 in. dbh are numbered, and species, dbh, and condition are recorded on the 1/20-ac plots. On the 1/5-ac plots, the same data are recorded for trees ≥4.5 in dbh. These plots provide an approximately 15% sample of each treatment. Seedlings ≥0.5 ft tall but <0.5 in. dbh are measured on three 1/1000-ac plots at the periphery of each 1/20-ac plot, beginning at approximately year 20 of the study.

Stand-level diameter distribution, number of trees per acre (TPA), total volume (ft^3/ac, for trees ≥4.5 in. dbh), BA, and regeneration stocking and density are calculated using the plot data. Stocking is a measure of how well seedlings are distributed across sample plots and is defined as the percentage of 1/1000-ac plots that have at least one seedling. Additional variables such as species composition, growth, and mortality also are determined.

We calculated value of standing inventory after the most recent harvest and value of each harvest. Value of standing inventory uses the commercial volume data from the post-harvest compartment inventory and stumpage prices for the year of the inventory. Each harvest was valued at stumpage prices for the appropriate year. An annual market (nominal) price series (1951–93) by species and product was created from annual reports of sales on the PEF and augmented with prices reported by the Maine Forest Service. Effects of inflation were eliminated by adjusting nominal prices by the Producer Price Index (all commodity). All values are reported in 1982 dollars. Present value of gross harvest revenues (discounted cash flow) were calculated at two real discount rates: 2% and 4%.

Between-treatment comparisons of overstory data were made prior to the first cut (year 0) and after the third cut (year 40–45) using analysis of variance (ANOVA) (ANOVA, Proc GLM, SAS Release 8.02, SAS Institute, Inc., Cary, NC), with $df = 1$ and $\alpha = 0.10$. Within-treatment comparisons were made between year 0 and year 40–45 data. To facilitate structural comparisons, diameter classes were defined as sapling (1–4 in. dbh), poletimber (5–8 in.), small sawtimber (9–12 in.) and medium–large sawtimber (>12 in.). BA data were analyzed for trees ≥4.5 in. dbh only, due to missing sapling data in the first DL inventory. Regeneration data were compared prior to the third cutting. When total values for volume and BA were significant ($P < 0.10$), percentages were analyzed for component species or size classes. An arcsine transformation was applied to percentage data (expressed as a proportion) prior to analysis (Freese 1967). The Northeastern Variant of the USDA Forest Service Forest Vegetation Simulator (FVS) (Bush 1995, Teck et al. 1996) was used to project future stand conditions, for the purpose of evaluating the feasibility of another harvest on a 20-year interval.

Results

Between-Treatment

A comparison of structure and composition revealed no significant differences in treatments at year 0 (Table 1, Figure 1). However, growth dynamics over the first 40 years of the study were different for the two treatments (Table 2). Although gross growth did not differ, net volume growth was significantly greater in the DL treatment ($P = 0.01$) (although the actual difference is not great, low variability resulted in a significant result). Assessment of the distribution of net growth across size classes reveals that this difference is primarily due to significantly greater ingrowth ($P = 0.03$) and small sawtimber growth in the DL treatment ($P < 0.01$). Medium–large sawtimber net growth was less in the DL stands ($P = 0.02$).

Total harvest volume ($P = 0.14$) did not differ by treatment, although small sawtimber harvest was greater in the DL stands ($P = 0.04$). Present value of removals for the first three harvests combined was significantly greater in the DL stands ($P = 0.05$–0.07) (Table 3). Inventory value after the third diameter-limit cut was less than 15% that of the SC stands ($P = 0.07$), but total value accumulated over the measurement period (harvest plus residual) did not differ by treatment ($P = 0.98$).

There were significant treatment differences in structure and quality after the third harvest (Table 1). Total volume was less in the DL stands ($P = 0.01$), and the amount ($P < 0.01$) and proportion ($P = 0.03$) of unmerchantable (cull) timber was greater. The proportion of stand volume in the smallest (poletimber) size classes was greater in the DL than in the SC ($P = 0.02$), and the amount ($P < 0.01$) and proportion ($P = 0.01$) of medium–large sawtimber was less. There were almost no merchantable trees in the medium–large sawtimber classes in the postcut DL stands (Figure 2). Additionally, total BA was lower in the DL ($P = 0.02$), although neither total live (Table 1) nor merchantable tree (data not shown) species composition differed by treatment.

Although total number of trees per acre did not differ between treatments after the third cut, stem densities of the small ($P = 0.04$) and medium–large ($P < 0.01$) sawtimber classes were lower in the DL than SC stands. There was, in fact, less than one medium–large sawtimber tree per acre in the DL stands, while stem density in these classes of the SC stands exceeded 20 trees/ac. The numbers of saplings and poles did not differ between treatments.

Regeneration responses in this study have been highly variable, and there were few statistically significant outcomes at either 5 or 10 years after harvests in the SC and DL stands (Brissette 1996). With data from two additional inventories, it is evident that the density of hardwood regeneration peaked about 10 years after harvest, while softwoods peaked about 5 years later (Figure 3). The greatest differences in seedling density between the SC and DL treatments occurred 15 years after harvest (Figure 3), but there were few statistical differences at that time (Table 4). Although there was abundant regeneration in both treatments, total regeneration in SC was twice that in DL ($P = 0.10$). Regeneration in both treatments was dominated by softwoods, which made up 80% or more of the total. The most abundant species were eastern hemlock in the SC treatment, and balsam fir in the DL treatment.

At regeneration inventories 5 and 10 years after the second harvest, there were no differences in stocking between DL and SC treatments (Brissette 1996). Likewise, there were no differences in stocking for inventories conducted 15 and 20 years after the second harvest (data not shown).

Within-Treatment

Stand volume and BA were significantly lower in both treatments after three entries than they had been at year 0

Table 1. Results of ANOVA of means prior to cut 1 and after cut 3 in the SC and DL treatments on the Penobscot Experimental Forest. Asterisks indicate significance at $\alpha = 0.10$.

	SC	DL	SE	*P*-value
Pre Cut 1				
Trees per acre	1,870.3	Missing data	–	–
Saplings	1,540.2	Missing data	–	–
Poletimber	220.4	227.1	19.1	0.83
Small sawtimber	88.1	84.2	14.0	0.86
Med.–large sawtimber	21.8	17.7	3.9	0.76
Volume (ft^3/ac)	2,163.0	2,095.0	187.1	0.82
Poletimber	685.0	746.0	64.5	0.57
Small sawtimber	951.5	922.0	151.8	0.90
Med.–large sawtimber	526.5	427.0	107.0	0.58
Cull volume	135.6	152.6	16.0	0.65
Percent cull	6.2	7.3	0.8	0.42
Basal area (ft^2/ac, ≥4.5 in. dbh)	122.5	117.0	9.6	0.73
Balsam fir (%)	6.7	11.1	4.3	0.55
Spruce species (%)	16.8	21.0	1.5	0.17
Eastern hemlock (%)	56.2	39.5	10.5	0.38
Northern white-cedar (%)	12.8	9.0	2.3	0.36
Paper birch (%)	1.1	3.4	1.4	0.38
Red maple (%)	3.4	11.0	1.4	0.52
Other species (%)	2.9	5.0	3.4	0.71
Post Cut 3				
Trees per acre	2,028.6	1,511.3	634.3	0.62
Saplings	1,914.8	1,417.6	630.0	0.63
Poletimber	56.8	73.4	10.2	0.37
Small sawtimber	33.6	19.5	2.0	0.04*
Med.–large sawtimber	23.5	0.9	1.6	<0.01*
Volume (ft^3/ac)	1,256.1	464.3	56.3	0.01*
Poletimber	197.5	257.5	52.1	0.39
Percent	14.1	55.5	3.5	0.02*
Small sawtimber	410.5	165.5	18.6	0.01*
Percent	32.7	35.6	1.6	0.24
Med.–large sawtimber	648.0	42.0	36.9	<0.01*
Percent	51.6	9.1	3.0	0.01*
Cull volume	14.3	118.0	5.2	<0.01*
Percent cull	1.1	25.4	3.1	0.03*
Basal area (ft^2/ac, ≥4.5 in. dbh)	61.0	28.2	3.2	0.02*
Balsam fir (%)	4.3	4.0	2.3	0.92
Spruce species (%)	37.7	18.4	4.8	0.11
Eastern hemlock (%)	41.0	37.3	8.1	0.77
Northern white-cedar (%)	8.3	18.2	7.9	0.47
Paper birch (%)	2.2	5.2	0.9	0.16
Red maple (%)	5.0	6.8	2.0	0.59
Other species (%)	1.5	10.2	1.7	0.43

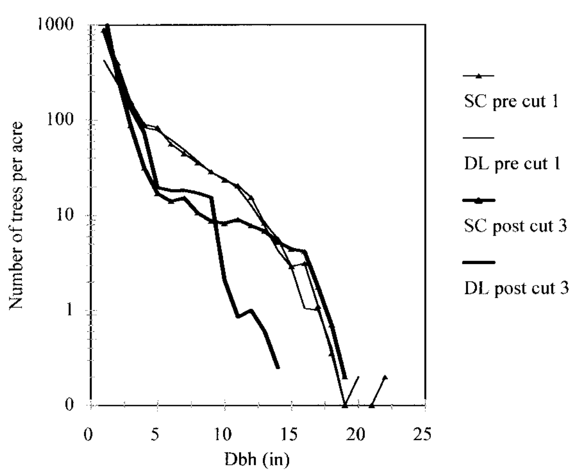

Figure 1. Diameter distributions of the SC and DL treatments on the Penobscot Experimental Forest, before cut 1 and after cut 3.

Table 2. Comparison of growth and removals following three harvests in the SC and DL treatments on the Penobscot Experimental Forest. Asterisks indicate significance at $\alpha = 0.10$.

	SC	DL	SE	*P*-value
Gross growth (ft^3/ac/yr)	50.7	54.4	2.7	0.31
Poletimber	8.0	11.0	1.6	0.24
Small sawtimber	10.1	31.3	2.0	0.02*
Med.–large sawtimber	32.7	12.1	2.2	0.02*
Mortality (ft^3/ac/yr)	10.4	11.6	2.4	0.77
Poletimber	5.7	8.2	1.6	0.38
Small sawtimber	2.6	2.9	0.7	0.82
Med.–large sawtimber	2.2	0.6	0.3	0.08*
Net growth (ft^3/ac/yr)	40.3	44.4	0.3	0.01*
Poletimber	2.4	3.5	1.9	0.70
Small sawtimber	7.4	29.3	1.3	<0.01*
Med.–large sawtimber	30.6	11.7	1.9	0.01*
Ingrowth (4.5 in. dbh, ft^3/ac/yr)	6.9	10.6	0.5	0.03*
Harvest (ft^3/ac)	2,518.2	3,527.8	300.8	0.14
Poletimber	580.0	643.3	44.2	0.42
Small sawtimber	837.1	1,966.8	157.3	0.04*
Med.–large sawtimber	1,101.2	917.8	102.6	0.33

Table 3. Comparison of financial data following three harvests in the SC and DL treatments on the Penobscot Experimental Forest (in 1982 dollars per acre). Asterisks indicate significance at $\alpha = 0.10$.

	SC	DL	SE	*P*-value
		($)		
Total harvest value	428	774	48	0.04*
Present value of gross harvest revenue (2%)	292	533	40	0.05*
Present value of gross harvest revenue (4%)	219	411	38	0.07*
Residual inventory value	409	59	68	0.07*
Accumulated value (harvest + inventory)	837	833	110	0.98

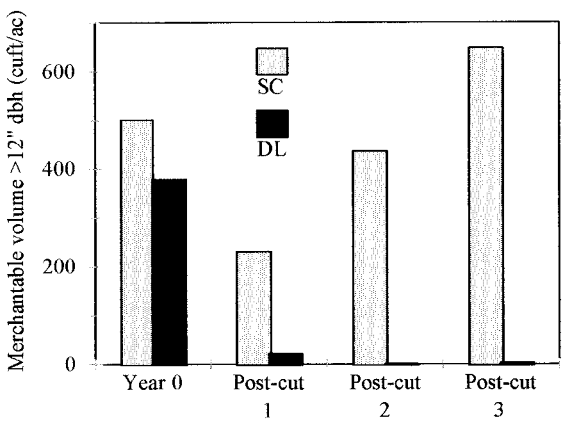

Figure 2. Merchantable medium–large sawtimber volume in the SC and DL treatments on the Penobscot Experimental Forest.

($P < 0.01$ to 0.03, Table 5). Though the percentage of unmerchantable volume decreased from 6 to 1% in the SC, cull increased from 7 to 25% in the DL treatment. There were no significant changes in species composition of trees ≥4.5 in. dbh after three diameter-limit removals, but the proportions of spruce species and paper birch in the SC treatment increased significantly during that time.

The FVS simulation model projected insufficient volume to sustain a harvest in either diameter-limit cut stand in 20 years. Assuming no increase in the number of cull stems, merchantable volume above the species-specific diameter limits is projected to be 1,038.1 and 1,061.9 in the two stands, i.e., approximately 88% of the target harvest volume. Total projected merchantable volume for the treatment 20 years after the most recent harvest (1,315.4 ft^3/ac) is less than that prior to the third cut (1,429.9 ft^3/ac). The model projected only 4.7 ft^3 of volume per merchantable tree at that time. Projected merchantable volume for the selection treatment (2,543.7 ft^3/ac) exceeds that prior to the third cut (1,734.8 ft^3/ac), indicating that another cut of the same volume can be sustained in 20 years. The average volume per merchantable tree in the SC treatment is projected to be 17.7 ft^3.

Discussion

The long-term study on the PEF provides resource managers with data to compare two treatments with the same cutting cycle but very different removal criteria. Though the structural goals and marking and species guidelines for the selection treatment are complex, they essentially prescribe a treatment in which unmerchantable and poor vigor trees are removed to create a high quality, vigorous stand with a wide distribution of ages and sizes. The diameter-limit treatment simply removes the biggest and best trees, without consideration of residual stand condition. Fortunately, the similarity of year 0 stand conditions in this experiment allows us to confidently attribute differences at years 40–45 to treatment.

Although total harvest volume did not differ significantly between the two treatments over the first 45 years of the study, present value of the diameter-limit removals exceeded that of the selection cuttings. This is indicative of the relatively larger size, better quality, and greater volume of trees removed in early diameter-limit entries. This practice of "taking the best and leaving the rest" resulted in substantially lower stand value after three entries. Although carrying less valuable growing stock reduces the opportunity cost (alternative rate of return × inventory value), e.g., from \$16.36/ac in the SC to \$2.36/ac in DL at 4% the first year postharvest, the low value and poor quality of the residual DL stands are indicative of less silvicultural flexibility and potential. This is consistent with Blum and Filip (1963), who noted that the advantages of greater first cut value and lower investment in standing timber in diameter-limit cut stands are offset by reduced residual growing stock quality, irregular stocking, and long intervals between harvests. Similarly, Sendak et al. (2000) found that diameter-limit cut northern hardwood stands had fewer grade 1 trees and less standing inventory value than selection cut stands.

Costs of inventory, marking and timber stand improvement (TSI) were not considered in comparing the two cutting methods. Although actual costs were not available, it is likely that it would cost more to apply selection than diameter-limit cutting. Preparing a selection cut requires collecting preharvest inventory data, preparing a marking guide, marking trees to cut, and felling unmerchantable timber. These costs were incurred, with the exception of TSI, as DL was applied on the PEF. However, a logger could satisfactorily apply a diameter-limit cut, and even collecting preharvest inventory data would not be required, avoiding sale preparation costs.

Niese et al. (1995) compared diameter-limit (40-year interval) and a selection-like cutting (10-year interval) in young, even-aged northern hardwood stands, and found that diameter-limit cutting resulted in greater harvest value, lower residual stand value, and lower accumulated value. Modeling by Nyland (2004) predicted a similar outcome for diameter-limit and selection cut uneven-aged northern hardwood stands. It is noteworthy that despite differences in stand age structure and/or forest type, those studies and ours produced similar results. This consistency in findings underscores the fact that the effects we have documented are treatment-related, and not restricted to a single forest type. Furthermore, Niese et al. (1995) stress the importance of residual stand value because it represents the amount and

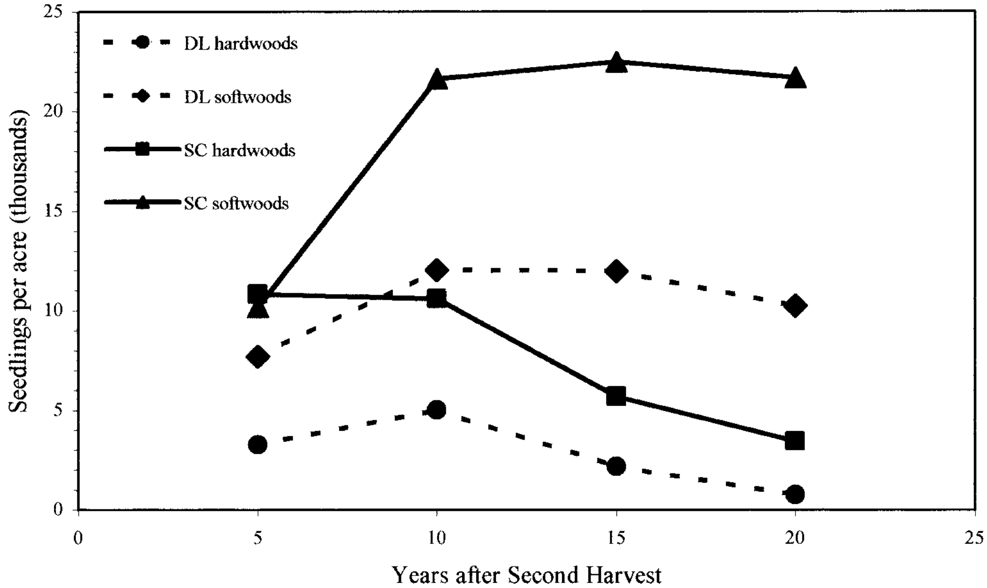

Figure 3. Regeneration density in the SC and DL treatments on the Penobscot Experimental Forest.

Table 4. Comparison of regeneration density in the SC and DL treatments on the Penobscot Experimental Forest, approximately 15 years following the second harvest. Asterisks indicate significance at $\alpha = 0.10$.

Species	SC	DL	SE	*P*-value
(seedlings/acre)				
Eastern hemlock	10,934	3,713	1,186	0.05*
Balsam fir	7,248	6,197	2,892	0.82
Spruce species	3,670	1,666	1,334	0.40
Total softwoods	22,492	11,981	5,040	0.28
Paper birch	2,888	354	1,746	0.41
Red maple	1,726	1,028	85	0.03*
Gray birch[a]	512	594	401	0.90
Total hardwoods	5,682	2,175	2,039	0.35
Total regeneration	28,174	14,156	3,434	0.10*

[a] *Betula populifolia* Marsh.

Table 5. Within-treatment comparison of means prior to cut 1 and after cut 3. Means are shown in Table 1. Asterisks indicate significance at $\alpha = 0.10$.

	Mean difference[a]	SE	*P*-value
SC			
Volume (ft^3/ac)	−906.9	106.21	0.03*
Poletimber	−507.5	44.76	0.02*
Small sawtimber	−541.0	16.50	<0.01*
Med.–large sawtimber	−121.5	90.67	0.44
Percent cull	−5.1	0.84	0.05*
Basal area (ft^2/ac, ≥4.5 in. dbh)	−61.5	4.17	<0.01*
Balsam fir (%)	−2.4	2.15	0.52
Spruce spp. (%)	+20.9	4.80	0.09*
Eastern hemlock (%)	−15.2	10.53	0.38
Northern white-cedar (%)	−4.5	2.45	0.32
Paper birch (%)	+1.1	0.04	<0.01*
Red maple (%)	+1.6	0.51	0.52
Other (%)	−1.4	0.09	<0.01*
DL			
Volume (ft^3/acre)	−1,630.7	163.96	0.02*
Poletimber	−488.5	69.79	0.04*
Small sawtimber	−756.5	152.01	0.07*
Med.–large sawtimber	−385.0	67.68	0.06*
Percent cull	+18.1	3.10	0.05*
Basal area (ft^2/ac, ≥4.5 in. dbh)	−88.8	9.36	0.02*
Balsam fir (%)	−7.0	4.42	0.37
Spruce spp. (%)	−2.6	1.98	0.44
Eastern hemlock (%)	−2.2	10.59	0.90
Northern white-cedar (%)	+9.2	7.89	0.50
Paper birch (%)	+1.8	1.73	0.54
Red maple (%)	−4.2	2.48	0.35
Other (%)	+5.2	5.88	0.59

[a] Mean difference = Post-cut 3 – Pre-cut 1.

quality of growing stock and thus ability to provide sustained, high-value harvests. Their analysis of accumulated value led them to conclude that diameter-limit is less desirable than selection cutting for high-quality sawlog production or sustained timber yield.

It is interesting that although total harvest volume did not differ by treatment, small sawtimber removals were greater in the DL than SC stands. This fact is undoubtedly due to ingrowth into these classes from the released poles, consistent with Hutnik (1958) and Blum and Filip (1963), who found greater ingrowth but lower accretion in diameter-limit cut hardwood stands. There was a dearth of medium–large sawtimber volume after the first diameter-limit cut in the present study. Large trees were simply not available for harvest in the diameter-limit cut stands after the first entry. This structure also likely accounts for lower gross and net growth in the medium–large sawtimber classes of the DL stands. Similarly, lower medium–large sawtimber mortality in the DL stands can be attributed to the presence of little sawtimber volume, rather than a positive effect of treatment on survivorship.

The failure to remove unmerchantable trees or tend below the diameter limits contributed to an accumulation of cull timber in the DL stands. This is consistent with Hart (1964), who documented the buildup of defective and poor vigor trees in the diameter-limit demonstration plot on the

PEF (not one of the stands included in the study reported here). This problem was also documented by Strong et al. (1995) in diameter-limit cut even-aged northern hardwood stands. In fact, we found that percent cull increased significantly over time in the DL treatment, and exceeded 25% of total stand volume after the third diameter-limit cut. Percent cull decreased over time in the selection treatment, and was only 1% in year 40 of the experiment. This abundance of unmerchantable growing stock in the DL stands (118.0 ft^3/ac versus 14.3 ft^3/ac in the SC stands) and the trend of increasing percent cull over time in that treatment suggest a loss of past and potential future production and value. This problem will persist as long as cull trees are occupying growing space that could otherwise be used to support merchantable timber and are competing for resources with nearby sound trees and regeneration.

The lower residual stand densities resulting from the DL treatment are apparent in the significantly and substantially lower volume and BA values. Live volume of the DL stands after the third cut was about one-third that of the selection stands. Over the first 40 years of the study, lower density in the DL stands resulted in greater release of lower-stratum trees, as evidenced by the larger amount of ingrowth. This higher proportion of growth on small and relatively low-value trees compensates to some extent for the lower volume and growth of residual medium–large sawtimber. In fact, total net growth was higher in the DL than SC stands, a finding consistent with that of a long-term study of diameter-limit (variable 5- to 12-year cutting cycle) and selection cutting (5-year cutting cycle) in loblolly–shortleaf pine (*Pinus taeda* L.–*P. echinata* Mill.) (Baker and Bishop 1986).

The hypothesis advanced by Roach (1974) cannot yet be evaluated using the PEF data because the third cut was just applied. However, our findings suggest that stand condition 20 years from now will not support another diameter-limit cut of the volume, species, and quality harvested in the past. It should be noted that although DL harvest volumes have been maintained thus far, the lower limit of merchantability changed from 6.5 in. dbh at the beginning of the study to 5.5 and 4.5 in. dbh at the times of the second and third cuts, respectively. This change in removal criterion provided greater volume for harvest. Even so, one of the DL stands did not have sufficient merchantable volume for a third harvest until 25 years after the second cut. Without further decreases in the diameter limits, it is not likely that cutting can be continued at or close to a 20-year interval, a conclusion supported by model output.

Research conducted by Sokol et al. (2004), who studied long-term (100-year) growth rates of residual red spruce on the PEF, addresses one of the mechanisms for the nonsustainability of DL harvests. When compared to trees in stands treated with selection cutting, the DL residuals were smaller and slower growing throughout their lives. This suggests that the DL treatment selects against the most vigorous trees on a site. This is reasonable, since faster-growing trees become larger sooner and cross the diameter thresholds and thus are cut instead of slower-growing, less vigorous individuals of the same age class. This process results in the continual down-grading of vigor and growth in repeatedly diameter-limit cut stands, and suggests that the former growth and quality of the diameter-limit cut stands cannot be reclaimed if treatments continue as currently described.

It is interesting that the species compositions of the DL and SC treatments did not differ after the third harvest. We anticipated that the use of inflexible diameter limits would decrease the proportions of long-lived and potentially large trees such as spruce species and eastern hemlock. The similarity in species compositions between the treatments cannot be attributed to the retention of cull sawtimber, because merchantable trees species composition also did not differ. Thus, there is no evidence of a negative effect on species composition after 40 years of diameter-limit cutting in this study. Significant increases in spruce species and paper birch in the SC stands between years 0 and 40, and the lack of a significant change in DL species composition during that time, indicate a trend that if continued, may result in future differences between treatments.

The regeneration data provide important information about stand dynamics, particularly with regard to future composition and structure. Regeneration inventories started about 5 years after the second harvests in the DL and SC treatments. After those harvests, regeneration density peaked at 10–15 years. Seedling density declined after that as some seedlings grew into the sapling class and others died. That seedling density remained high through 20 years after the harvests, especially among the tolerant softwoods, suggests that many of them have not yet grown to a dbh of 0.5 in. Observations indicate that new seedlings continue to become established in these stands, although at a much slower rate than during the first several years after harvest. Future research on the growth and composition of this new cohort will enable us to better assess long-term sustainability of species and structure.

Conclusion

The long-term experiment on the PEF is ideally suited for comparison of diameter-limit and selection cutting. Data obtained over the course of the experiment, in which both treatments were applied at 20-year intervals to stands with similar initial conditions, establish the consequences of uneven-aged silviculture and diameter-limit cutting. Diameter-limit cutting yielded greater present values of harvest revenues than the selection method, and the treatments were not differentiated in terms of accumulated value or species composition. However, diameter-limit cutting resulted in lower residual stand volume and value, a higher proportion of unmerchantable growing stock, less medium–large sawtimber growth and harvest, and less dense regeneration. These stand characteristics translate into fewer management options and less silvicultural flexibility. Short-term benefits of greater early value removals and ease and cost of application were offset by the creation of stand conditions that limit residual and potential future benefits.

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