Comparing selection system and diameter-limit cutting in uneven-aged northern hardwoods using computer simulation

Kimberly K. Bohn, Ralph D. Nyland, and Ruth D. Yanai

Abstract: Comparisons of selection system and diameter-limit cutting based on trials in specific settings have often yielded conflicting results. We used a simulation approach to evaluate sawtimber production over three cutting cycles on 10 sugar maple (*Acer saccharum* Marsh.) dominated plots of varying initial forest structure. Treatments on each plot included light, moderate, and heavy intensities of selection system silviculture and diameter-limit cutting. Harvested sawtimber volumes were initially higher on all plots using diameter-limit cutting, but selection system outperformed diameter-limit cutting at later entries on 7 of the 10 plots. Volume differences between cutting types ranged among plots from 0.3 to 26 $m^3 \cdot ha^{-1}$, equating to a less than 1% to as much as a twofold difference. Average volumes from selection system at later entries were 20%–40% greater than diameter-limit cutting, due in part to consistent production in large sawtimber (≥46 cm). Yields from real stands could vary from these simulations where mortality losses (not modeled here) differ between treatments as a result of competition or logging damage. Findings suggest that cumulative sawtimber volumes from repeated selection system silviculture could eventually surpass that of diameter-limit cutting, but at a rate depending on initial stand conditions and harvesting intensity.

Résumé : Les comparaisons entre les systèmes de jardinage et de coupe à diamètre limite ont souvent produit des résultats divergents lorsqu'elles étaient basées sur des essais réalisés dans des cadres spécifiques. Nous avons utilisé une approche par simulation pour évaluer la production de bois de sciage au cours de trois cycles de coupe appliqués à 10 parcelles dominées par l'érable à sucre (*Acer saccharum* Marsh.) et qui se distinguaient par la structure initiale de la forêt. Les traitements simulés dans chaque parcelle comprenaient trois intensités (faible, modérée et forte) pour chaque système sylvicole. Le volume de bois de sciage récolté était initialement plus élevé dans toutes les parcelles soumises à une coupe à diamètre limite, mais le rendement de la coupe de jardinage a dépassé celui de la coupe à diamètre limite lors d'interventions ultérieures dans 7 des 10 parcelles. Les différences de volume entre les types de coupe variaient de 0,3 à 26 $m^3 \cdot ha^{-1}$ selon la parcelle, ce qui correspond à de différence de moins de 1 % jusqu'à de différence double. Le volume moyen des interventions ultérieures de la coupe de jardinage étaient de 20 % à 40 % plus grand que celui de la coupe à diamètre limite, notamment grâce à la production soutenue de grosses billes de sciage (≥46 cm). Le rendement de peuplements réels peut être différent de ces simulations à cause des pertes dues à la mortalité (non simulées ici) qui peuvent varier selon le traitement en fonction de la compétition ou des blessures d'exploitation. Les résultats indiquent que le volume cumulé de bois de sciage provenant d'interventions répétées dans le cadre d'un système de jardinage pourrait éventuellement surpasser celui de la coupe à diamètre limite, mais à un rythme dépendant des conditions initiales du peuplement et de l'intensité de la récolte.

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Introduction

Diameter-limit cutting provides high sawtimber volumes at the first entry (Fajvan et al. 1998; Nyland 2001), but its long-term viability for management of uneven-aged hardwood forests has been challenged. Growth responses following an initial diameter-limit cut vary across field sites because of differences in initial stand density and the amount of ingrowth from sapling diameter classes (Beck 1981; Erickson et al. 1990; Miller and Smith 1991). Appalachian hardwoods that had high numbers of good-quality, fast-growing poles had high rates of volume growth after 23 and 30 cm diameter-limit cuts because the small trees moved into a harvestable status before the next entry (Smith and Lamson 1977; Beck 1981). In other cases, variation in sawtimber production has been associated with the progressive movement of deficiencies or excesses from smaller diameter classes into sawtimber sizes (Schuler 2004; Nyland 2005). Further, variations of initial diameter distributions across three northern hardwood stands led to a 50% difference in predicted cu-

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mulative sawtimber production (century-long harvest volumes plus that standing after the last entry) from simulated diameter-limit cutting (Nyland 2005). The consistency and levels of yields through time will thus depend on the stand structure, which is not controlled by this cutting method.

In contrast, single-tree selection system silviculture can provide fairly consistent sawtimber yields on a variety of sites because the stand is regulated using a target residual diameter distribution (Eyre and Zillgitt 1953; Arbogast 1957) and the cutting intensity is matched to an appropriate cutting cycle length (Hansen and Nyland 1987; Leak et al. 1987; Nyland 1998). Residual diameter distributions have been observed to be stable over multiple cutting cycles (Leak 1996; Schwartz et al. 2005; Bohn and Nyland 2006). In the same simulation study as described above, Nyland (2005) found that cumulative sawtimber production over a 90 year period varied by only a 10% when modeling three different stands using selection system. Also, post-cutting basal areas of 11–21 $m^2 \cdot ha^{-1}$ provided similar levels of annual sawtimber production over cutting cycles ranging from 10 to 25 years where the cutting interval was appropriate to the residual stand density (Crow et al. 1981; Hansen and Nyland 1987). Proponents suggest that for these reasons, selection system would better maximize long-term sustainable volume production.

Still, recommendations for appropriate long-term management of uneven-aged northern hardwoods remain divided between selection system silviculture and diameter-limit cutting, often justified by the volumes obtained from only a single cutting cycle or from growth responses in only a single stand (Trimble 1971; Beck 1981; Heiligmann and Ward 1993). The few studies evaluating multiple cutting cycles showed mixed results (Erickson et al. 1990; Buongiorno et al. 2000; Nyland 2005), perhaps due to differences in attributes such as the diameter distribution, stand stocking, or species composition. All affect long-term stand development.

Computer simulation allows comparisons of long-term effects from different cutting practices in stands with identical initial structural conditions. We simulated both selection system silviculture and diameter-limit cutting for 10 northern hardwood plots with a range of initial densities, diameter distributions, and spatial distributions of trees. Our objectives were to evaluate these two cutting practices over multiple cutting cycles to quantify what effect stand conditions had on sawtimber production and harvest volumes. We evaluated differences in treatments by individual plot as well as averaged across all plots.

Methods

Site description

The uneven-aged stands used to define initial structural characteristics for our simulations are on the Allegheny Plateau in Cortland County, New York. Soils are Inceptisols, mainly Lordstown and Mardin series developed in glacial till (USDA Soil Conservation Service 1999). They are productive mesic, well-drained, coarse- to medium-textured loams and silt loams originating from siltstone and sandstone.

Species composition was typical of northern hardwoods. Each stand had sugar maple (*Acer saccharum* Marsh.) as the dominant species (70%–80% of stems in all size classes). American beech (*Fagus grandifolia* Ehrh.), striped maple (*Acer pensylvanicum* L.), hop-hornbeam (*Ostrya virginiana* (Mill) K. Koch), white ash (*Fraxinus americana* L.), basswood (*Tilia americana* L.), yellow birch (*Betula alleghaniensis* Britt.), red maple (*Acer rubrum* L.), black cherry (*Prunus serotina* Ehrh.), and eastern hemlock (*Tsuga canadensis* (L.) Carr.) were minor components.

All stands had at least two partial cuttings over the past 50 years, with the most recent 10–15 years prior to data collection. Management included carefully controlled selection system silviculture, less formal partial cutting, and diameter-limit cutting (Table 1). Collectively, they represented the diversity of conditions that managers might encounter in the region.

Initial structural conditions

We mapped locations and recorded diameter at breast height (DBH) for all stems ≥5 cm DBH on ten 91 m × 91 m (0.85 ha) plots distributed across the five stands, with the number of plots per stand depending on stand area. The 10 plots varied in their diameter distributions, stocking (Fig. 1), and spatial structure. All plots had a reverse-J-shape diameter distribution of varying steepness and shape. Maximum diameters ranged from 56 to 76 cm. Within stands, disparate structural conditions were observed between plots, particularly in those stands that had unregulated partial cuts. *t* tests of basal area by size class on the 36 subplots within each 0.85 ha whole plot revealed significant differences (α = 0.10) in the pole classes for stands 1 and 5 and in the small sawtimber class for stands 3 and 5. Additionally, the spatial distribution of trees ranged from significantly clumped to significantly overdispersed, both between and within stands (Bohn 2005), which affected growth calculations in the simulation.

Simulation design

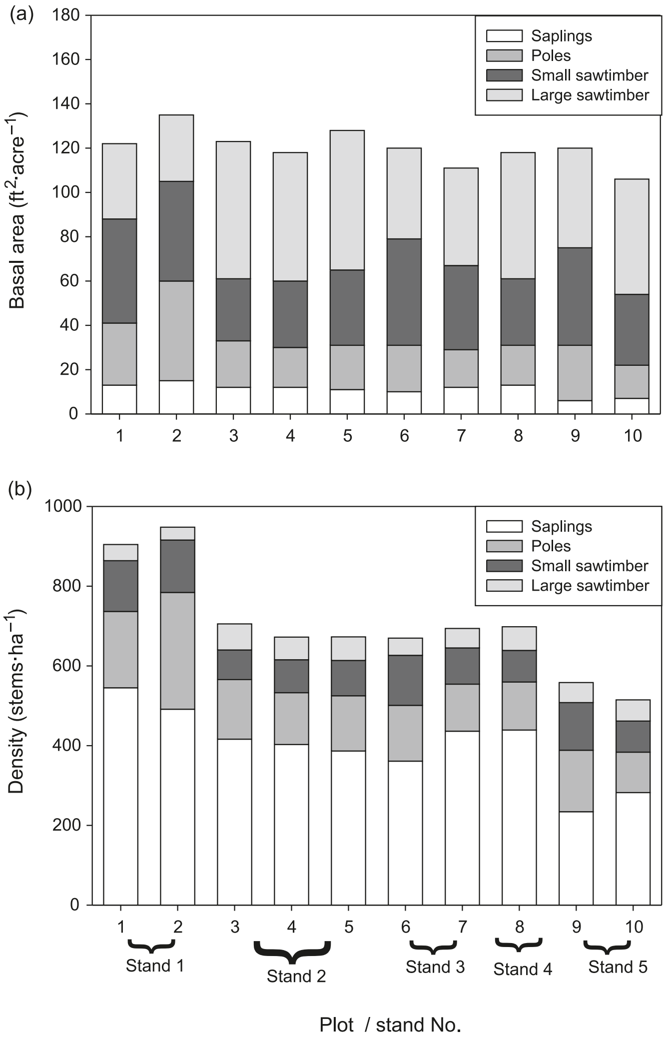
Hansen (1983) originally developed a simulator to test effects of diameter distribution and cutting cycle length on stand dynamics and volume production following selection system silviculture. He used calibration data from six uneven-aged stands dominated by sugar maple and on mesic soil conditions, including three sites used in this study. Past cutting ranged from true selection system to unregulated partial cuts, with residual basal areas of 6–30 $m^2 \cdot ha^{-1}$ (Hansen and Nyland (1987).

Our study utilized only the growth components of the Hansen simulator to build on previous assessments of uneven-aged northern hardwoods by Hansen and Nyland (1987), Davis (1988), and Nyland (2005). The original simulator uniformly distributed all trees within a size class across twenty-five 0.04 ha plots and then randomly assigned diameters to those trees. It calculated tree growth by 5 year intervals using basal area of the 0.04 ha plot as a competition factor to modify diameter increment. Stand-level production was the sum of growth across the simulated plots. Davis (1988) modified the simulator to accept a user-defined initial diameter distribution based on actual measured stand conditions but with trees still assigned uniformly among the 25 subplots. We added a spatial component that uses coordinates of measured trees from the stem maps to define the initial structural conditions within each subplot. To account for in-

Table 1. Location and cutting history of the mapped stands used to initiate the simulation at the Cuyler Hill State Forest south of Cuyler, New York (stands 1–4), and at the Secord Hill State Forest south of Truxton, New York (stand 5).

Stand	Latitude	Longitude	Cutting history	Stand size (ha)	Post-cut basal area ($m^2 \cdot ha^{-1}$)
1	42°41′8.5′′N	75°53′55.3”W	Diameter-limit, 1991	6.5	20
2	42°39′47.0′′N	75°54′6.4”W	Selection system, 1993	10.0	18
3	42°39′48.3′′N	75°55′8.8”W	Unregulated partial cut, 1991	6.2	21
4	42°39′42.6′′N	75°55′16.6”W	Selection system, 1981	3.2	16
5	42°38′43.7′′N	75°57′35.0”W	Unregulated partial cut, 1989	4.5	21

Fig. 1. (*a*) Basal area and (*b*) density of saplings, poles, small sawtimber, and large sawtimber on the 10 plots used for the simulations.



tertree competition, we modified the simulator to calculate the local basal area around each subject tree rather than by subplot. This made the estimates of stand-level production sensitive to small-scale variations in spatial structure. An initial sensitivity analysis of four plots having nonuniform tree distributions showed that this approach reduced total basal area growth and sawtimber production by 10%–20% compared with the original Hansen methodology.

Simulated cutting treatment

For each 0.85 ha plot, we simulated three intensities of selection system cutting and four intensities of diameter-limit cutting over three cutting cycles. The diameter-limit treatments had a minimum cutting diameter of 30, 36, 41, and 46 cm DBH (referred to as D30, D36, D41, and D46), with all trees of that size or larger removed. Selection system treatments reduced the basal area to 14, 16, and 21 $m^2 \cdot ha^{-1}$ (referred to as S14, S16, and S21). For these treatments, we compared the diameter distribution on each plot with those recommended by Eyre and Zillgitt (1953) andArbogast (1957) for a residual basal area of 21 $m^2 \cdot ha^{-1}$ and by Hansen and Nyland (1987) for 14 and 16 $m^2 \cdot ha^{-1}$ (Fig. 2). Then, we developed marking guides to indicate numbers of trees to cut within 5–15 cm diameter classes.

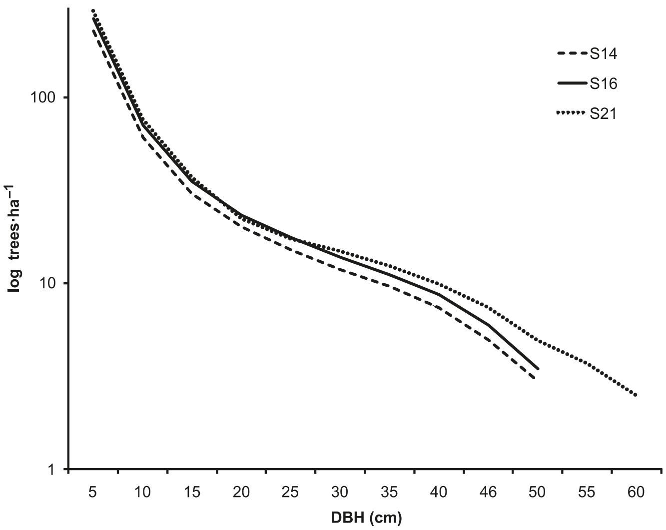
To automate the marking procedure, we developed a computer program that selected trees for cutting based on a user-specified maximum residual diameter, the numbers of trees to cut per diameter class, and a set of spacing criteria. Trees were grouped by size class (saplings: 5–14.9 cm, poles: 15–29.9 cm, small sawsawtimber: 30–45.9 cm, and large sawtimber: ≥46 cm), and starting with the largest size classes and working downward, trees were selected for possible removal if the distance to a neighbor of similar size was small enough to cause crown overlap or future crown overlap based on diameter–crown relationships for sugar maple by Kenefic and Nyland (1999). The pairs were sorted by distance apart and a subroutine determined if cutting one of them would create a gap larger than the average desired spacing among residual trees of that size. If not, the tree was removed. If so, the tree was retained for continued growth. If too few trees were taken from a diameter class to satisfy the residual stand criteria, the remaining trees were reevaluated for crown overlap with ones of the next smallest size class, and additional trees were removed if they released smaller ones. This process continued until the specified number had been taken from each diameter class.

The automated harvesting routine was developed to implement decision criteria that would be used in the field, namely reducing local crowding within and between size classes while maintaining an even distribution of all size classes across the stand. To verify the accuracy of this simulated procedure, we actually marked four plots using standard field methods. In all cases, the automated system selected exactly the same sawtimber trees, and the choice of poles varied by at most three trees per plot.

Simulated stand development

We grouped treatments by intensity, heavy (S14 and D30), moderate (S16 and D36, D41), or light (S21 and D46), based on similarity in residual basal area after the initial treatment and the time needed between entries to realize another operable cut (21 $m^3 \cdot ha^{-1}$). We used a 25 year period for heavy-

Fig. 2. Target residual diameter distributions using selection system after Eyre and Zillgitt (1953) and Arbogast (1957) for residual basal area of 21 $m^2 \cdot ha^{-1}$ (S21) and Hansen (1983) for 14 $m^2 \cdot ha^{-1}$ (S14) and 16 $m^2 \cdot ha^{-1}$ (S16).



intensity cuts, 20 years for moderate-intensity cuts, and 10 years for light-intensity cuts. These intervals coincide with the cycles recommended by Arbogast (1957) and Hansen and Nyland (1987) for selection system and the minimum time needed for sufficient growth following diameter-limit cuts.

Given the predominance of sugar maple in our sample stands, coupled with the absence of existing growth equations for less shade-tolerant species in uneven-aged northern hardwoods, we assumed a uniform species composition. This simplified the approach by eliminating species composition as a variable affecting the outcome of the silvicultural treatments. We simulated growth of all trees using equations derived for sugar maple (Hansen and Nyland 1987).

We did not include either ingrowth to sapling sizes or mortality in our model. These omissions introduce some biases, but they also simplify the interpretation of the outcomes of the simulated cutting. The spatially explicit nature of the data would have required simulating a stochastic addition and removal of trees for ingrowth and mortality. This would have diminished our ability to detect differences in production induced by imposing cutting treatments on plots of identical structure, which was the variable of interest in this study.

Since the tree lists included diameters down to 5 cm DBH, they accounted for all trees likely to grow to sawtimber sizes within a 50 year time period represented by the longest simulation. Recruitment of new trees into sawtimber sizes was therefore not an issue as long as we did not extend the simulations beyond three entries. Ingrowth would provide some level of competition to existing stems, and we made calculations estimating the magnitude of this omission using plots 1, 3, and 6 representing histories of diameter-limit cutting, selection system, and partial cutting, respectively. For these tests, ingrowth densities following the first simulated harvest were based on those reported by Hansen and Nyland (1987) for conditions similar to our simulated cuts. For simplicity, ingrowth stems were assigned a DBH of 2.5 cm and distributed uniformly across the plot. Individual tree growth was recalculated using the additional basal area contributed by these trees, and total sawtimber production was summed and compared with values without ingrowth.

Omitting mortality somewhat overpredicts sawtimber production. It is likely that mortality rates may differ following selection system and diameter-limit cutting; however, we neither had nor found empirical information to appropriately model this. We chose not to arbitrarily assign different rates to our treatments because these would affect our results according to the rates that we assigned to them rather than clarify the effects of the cutting treatments themselves on production and yield. The consequences of this omission are further addressed in the Discussion section.

Data analyses

We calculated sawtimber production and harvest volumes by 2.54 cm classes using volume equations for Lake State sugar maple (Gevorkiantz and Olsen 1955) and summed them by small (trees ≥30 and <46 cm DBH), large (trees ≥46 cm DBH), and total sawtimber (trees ≥30 cm). These equations calculate volume in board feet using the international 1/4 inch rule, which was then converted to cubic metres. Cumulative harvest volume equaled the total volumes from three consecutive entries. To compare treatments with different length cycles, we annualized sawtimber production (cubic metres per hectare per year) for the two growth periods and for harvest volumes after the second and third cuts.

We used repeated-measures ANOVA with Proc Mixed (SAS Institute Inc. 1999) to evaluate treatment effects on average annualized production for total sawtimber and large sawtimber using plots as the experimental units. We tested main effects of treatment ($n = 7$, representing the four diameter-limit and three selection system treatments) and time ($n = 2$, representing the two growth periods between harvests) as well as the treatment × time interaction ($n = 14$) and made multiple comparisons using an adjusted Tukey HSD test at $\alpha = 0.10$. Plot was included as a random effect. A similar but separate procedure was used for annualized harvest volume for the second and third cutting cycles. The final cumulative harvest volumes were analyzed by cutting intensity with a one-way ANOVA, including plot as a blocking factor.

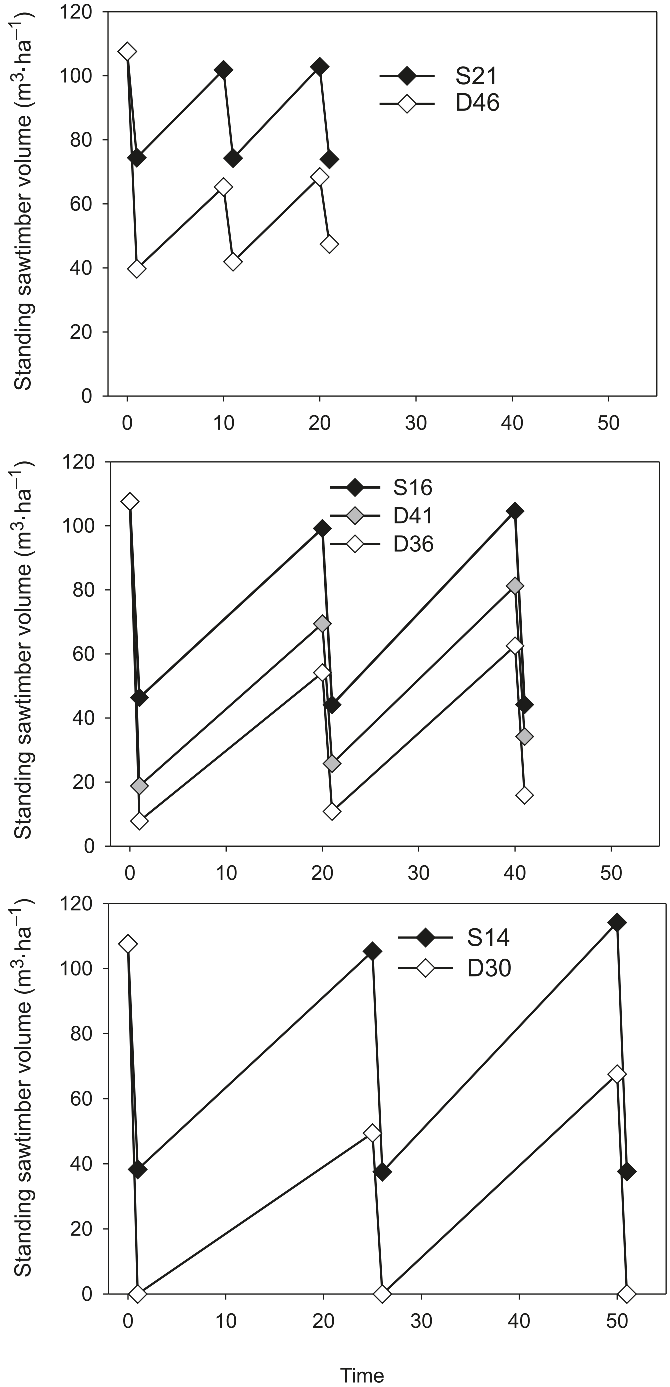
To assess within-treatment variability across plots, we calculated the coefficient of variation of the mean harvest volume by treatment. To evaluate how different treatments varied on individual plots, we subtracted the harvest volume derived by diameter-limit cutting from that using selection system of similar intensity.

Results

Average sawtimber production and harvest volumes

The initial diameter-limit cuttings yielded 35%–65% more total sawtimber volume (trees ≥30 cm) than selection system of comparable intensity and as a consequence reduced residual standing volume far below that of selection system. During the following growth and harvest periods, the standing volume in diameter-limit stands was always less than in the selection system treatments (Fig. 3). Over the range of conditions used in the simulations, average annualized values for

Fig. 3. Standing sawtimber volume (trees >30 cm) by time interval. Lower ends of the sawtooth lines represents the average residual stand volume after harvesting and the upper ends the average stand volume after each growth cycle. Minimum cutting diameter for diameter-limit treatments: 30 cm DBH (D30), 36 cm DBH (D36), 41 cm DBH (D41), and 46 cm DBH (D46); residual basal area for selection system treatments: 14 m^2·ha^{-1} (S14), 16 m^2·ha^{-1} (S16), and 21 m^2·ha^{-1} (S21).



total sawtimber production between cuttings as well as annualized harvest volumes differed by treatment and time ($p = 0.001$ for both) (Fig. 4). At the first growth period, average sawtimber production rates were consistent (2.6–2.7 m^3·ha^{-1}·year^{-1}) for the three selection system treatments, although these values were not always significantly higher than that produced by diameter-limit cutting, which ranged from1.9 to 2.6 m^3·ha^{-1}·year^{-1} (Fig. 4*a*). Annualized production increased by 0.1–0.7 m^3·ha^{-1}·year^{-1} for all treatments during the second growth interval (Fig. 4*b*) but significantly so for only for the heavier intensity treatments: D30 (p = 0.001), S14 (p = 0.02), and S16 (p = 0.02). Annualized harvests also significantly increased by 0.3 m^3·ha^{-1}·year^{-1} for all selection system treatments and by 0.7 m^3·ha^{-1}·year^{-1} for the heavy diameter-limit cutting. Average sawtimber harvest volumes from the selection system treatments were significantly higher than from diameter-limit cutting in all cases except for the light diameter-limit cutting at the second entry.

Mean annualized production and harvest of large sawtimber (trees >46 cm) differed significantly by treatment (p = 0.001) but not by time. Volumes increased significantly with decreasing intensity of diameter-limit treatment but not across the different selection system treatments (Fig. 4). Annualized volumes from the light-intensity diameter-limit cut were not significantly lower than from selection system. Production of large sawtimber was greatly reduced after the initial moderate and heavy diameter-limit cutting (Fig. 4), while it accounted for 80%–90% of the total sawtimber produced and harvested under selection system silviculture during both growth periods.

Average cumulative harvest volumes

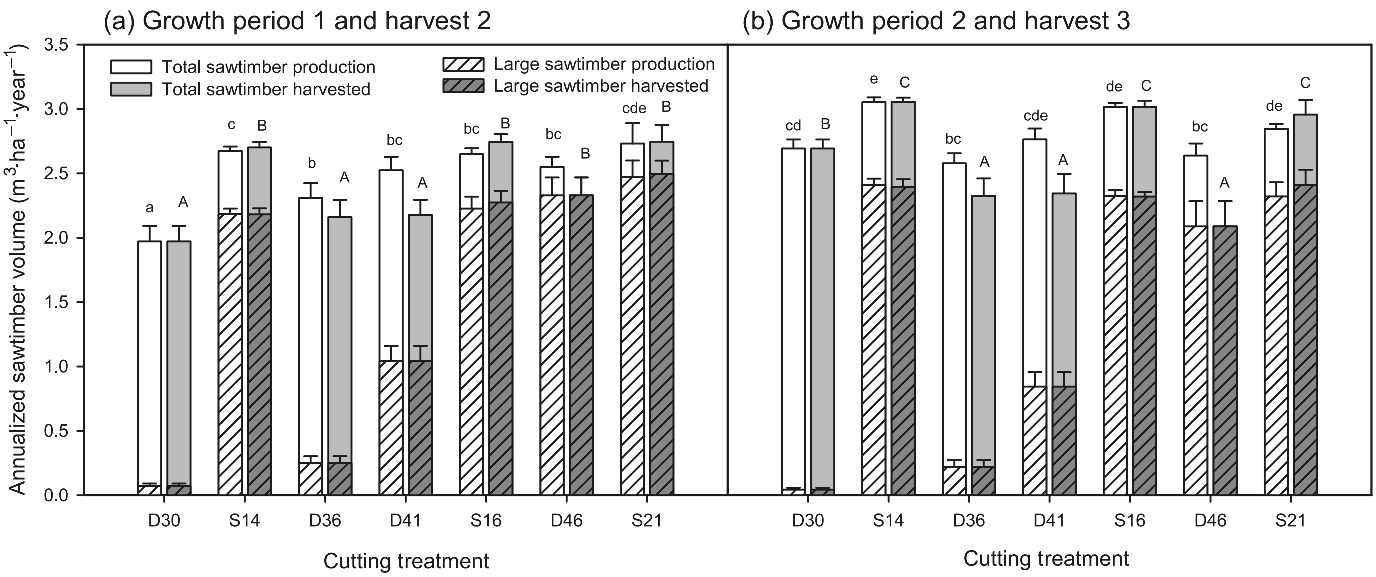
While the initial advantage of diameter-limit cutting diminished over the three cutting cycles, greater sawtimber volumes from selection system at later times did not fully compensate for that removed during the first diameter-limit cuts (Fig. 5). Compared with diameter-limit cutting, cumulative total sawtimber harvested for three entries was about 21 m^3·ha^{-1} less for the light selection system treatment and 10 and 15 m^3·ha^{-1} less for the moderate and heavy treatments, respectively ($p < 0.006$ for all intensities). Moderate and heavy selection system treatments yielded more cumulative harvest of large sawtimber, even by the second cutting cycle (Fig. 6). Light diameter-limit cutting provided a greater cumulative harvest of large sawtimber than light selection system, primarily due to removing more volume with the first entry (Fig. 6).

Sawtimber volumes across plots

We used the coefficient of variation to assess within-treatment differences in harvest volumes across the 10 plots (Ta-Table 2). The coefficient of variation decreased with repeated selection system cutting. Although the plots started with different initial conditions, selection system resulted in more consistent residual diameter distributions across the plots with each progressive cutting cycle. In contrast, with repeated diameter-limit cutting, the variability across plots generally increased, except for heavy-intensity diameter-limit cutting at the third harvest. In general, the coefficient of variation was two to four times higher for diameter-limit cuts than for selection system of similar intensity.

When we compared the volume harvested by diameter-limit cutting with that from selection system of comparable intensity, differences varied by plot (Fig. 7). Initially, differences reflected the variation in initial stocking of large sawtimber, likely due to effects of past cutting practices in stands

Fig. 4. Annualized large and total sawtimber production and sawtimber harvest following (*a*) the first growth period and second harvest and (*b*) the second growth period and third harvest. Means for annualized production with different lowercase letters and means for annualized harvest with different uppercase letters are significantly different at $\alpha = 0.10$. Minimum cutting diameter for diameter-limit treatments: 30 cm DBH (D30), 36 cm DBH (D36), 41 cm DBH (D41), and 46 cm DBH (D46); residual basal area for selection system treatments: 14 $m^2 \cdot ha^{-1}$ (S14), 16 $m^2 \cdot ha^{-1}$ (S16), and 21 $m^2 \cdot ha^{-1}$ (S21).



used to initiate the simulation (Fig. 1; Table1). In the simulation, the first diameter-limit cutting yielded more volume than selection system in all cases, and particularly on plots with a history of selection system silviculture (plots 3,4, 5, and 8). Those plots had more standing sawtimber to remove compared with plots with a history of diameter-limit (plots 1 and 2) or informal partial cutting (plots 6, 7, 9, and 10).

As described above, average harvest volumes at later entries were greater for selection system than for diameter-limit cutting, but the differences in harvest volumes between cutting strategies on any one plot ranged from –6.2 to as much as +26 $m^3 \cdot ha^{-1}$ (Fig. 7). Volumes from diameter-limit cutting exceeded that for selection system on only one plot. Differences in cumulative harvest volumes between the two types of treatments also varied considerably from nearly negligible differences to more than 40 $m^3 \cdot ha^{-1}$ over the three cutting cycles.

Discussion

Influence of initial structure on long-term comparisons

The need for caution in judging the success of diameter-limit cutting or selection system silviculture based on a single field trial is demonstrated by the range of responses obtained across plots in these simulations (Fig. 7). While selection system generally provided greater sawtimber volumes than diameter-limit cutting at later entries, the difference in volumes varied considerably across the plots, in some cases giving the opposite result. Harvest volumes for the second heavy diameter-limit cutting were highest, relative to selection system cutting, on plot 2 and particularly on plot 9 (Fig. 6), where a high residual basal area of trees just below the threshold cutting diameter (Fig. 1) moved appreciably from large poles into small sawtimber sizes. Results on those plots were consistent with field observations reported by Smith and Lamson (1977) and Beck (1981), although that was not the predominant structural condition mapped across our sample stands.

Diameter-limit cutting gave good results when pole densities were high and treatments were heavy enough to result in ample growing space for their release. Treatment comparisons were more variable for moderate cutting intensities even under similar diameter structures. For example, on plots 1 and 2, which had the highest initial basal area of poles and small sawtimber, selection system did outperform diameter-limit cutting, but on plots 6 and 9, which had only slightly lower initial basal area in those classes, diameter-limit cutting gave nearly comparable or better results at later entries. Plots 1 and 2 had more clustered spatial distribution of poles and small sawtimber as compared with plots 1 and 2 (Bohn 2005), and these differences in spatial structure resulted in more competition and less growth using our spatially explicit competition index. Thus, under more moderate cutting, both initial diameter structure and spatial structure influenced volume production and comparisons between different cutting treatments.

Any continued advantage from diameter-limit cutting would depend on consistent ingrowth into small sawtimber sizes from a buildup of trees just below the threshold cutting diameter. Roach (1974) theorized that crowding among poles would eventually dampen recruitment of saplings, slow growth within the pole classes, and reduce ingrowth to sawtimber sizes; however, Leak (1996) noted that this would not occur after a single cutting. Likewise, Davis (1988) and Kenefic et al. (2005) suggested that sawtimber yields may not drop below that of selection system cutting until after two or three consecutive diameter-limit cuttings. In our simulation of diameter-limit cutting, high levels of competition did slow

Fig. 5. Mean cumulative harvest volume of all sawtimber ≥30 cm by cutting cycle for (*a*) light-, (*b*) moderate-, and (*c*) heavy-intensity cuttings. The uppermost standard error bar is associated with cumulative harvest and the others represent individual harvests. Minimum cutting diameter for diameter-limit treatments: 30 cm DBH (D30), 36 cm DBH (D36), 41 cm DBH (D41), and 46 cm DBH (D46); residual basal area for selection system treatments: 14 $m^2 \cdot ha^{-1}$ (S14), 16 $m^2 \cdot ha^{-1}$ (S16), and 21 $m^2 \cdot ha^{-1}$ (S21).

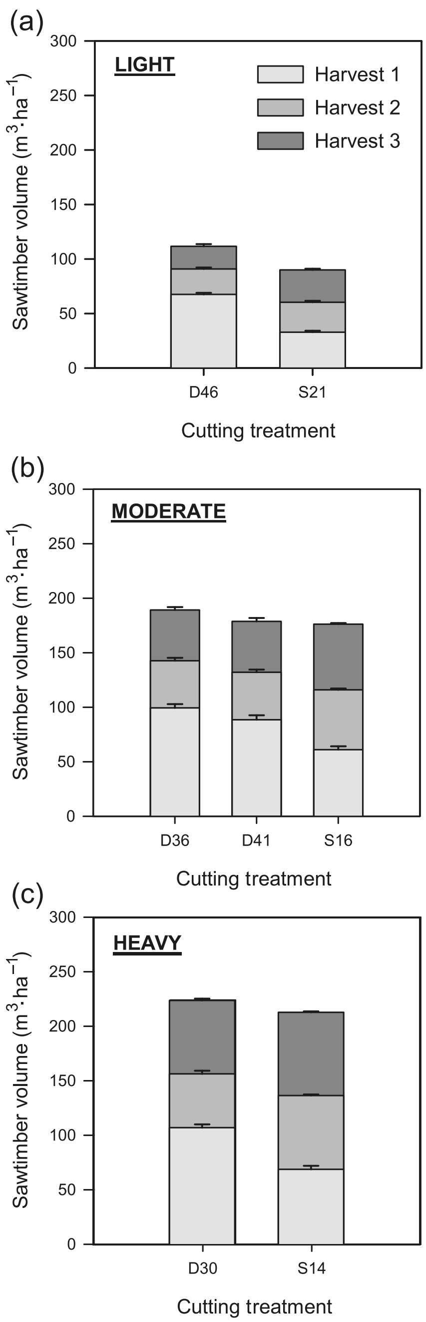
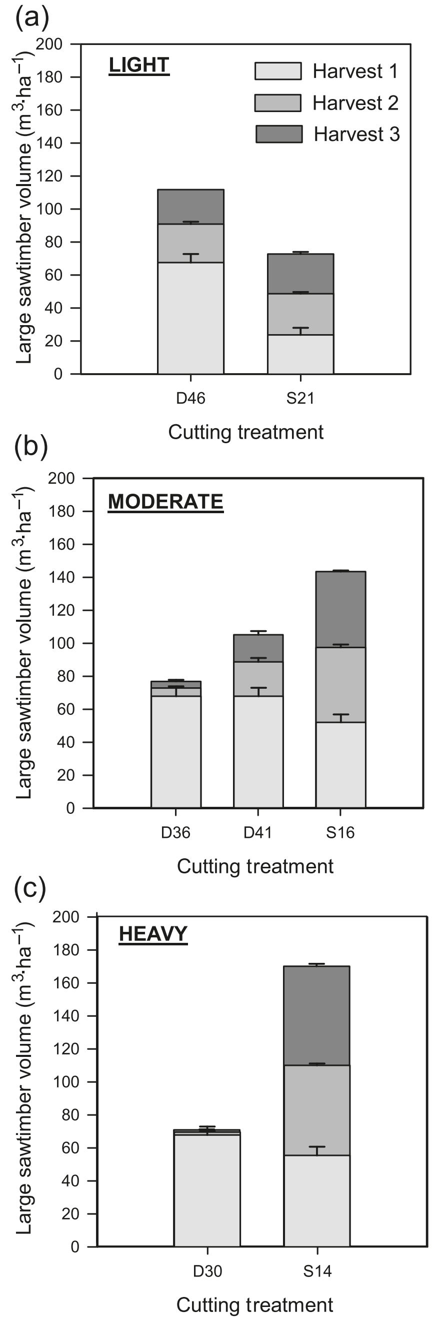


Fig. 6. Mean cumulative harvest volume of large sawtimber >46 cm by cutting cycle after the final entry for (*a*) light-, (*b*) moderate-, and (*c*) heavy-intensity cuttings. The uppermost standard error bar is associated with the cumulative harvest and the others represent individual harvests. Minimum cutting diameter for diameter-limit treatments: 30 cm DBH (D30), 36 cm DBH (D36), 41 cm DBH (D41), and 46 cm DBH (D46); residual basal area for selection system treatments: 14 $m^2 \cdot ha^{-1}$ (S14), 16 $m^2 \cdot ha^{-1}$ (S16), and 21 $m^2 \cdot ha^{-1}$ (S21).



growth of a few trees into larger sizes, with some trees not growing more than 0.1 cm during the entire simulation period, yet total sawtimber harvests from diameter-limit cutting still did not decrease substantially compared with selection system on four of the plots during the second or 3third diameter-limit cuts. Within the context of our simulation, we expect that cumulative harvest volumes from selection system would eventually surpass those from diameter-limit cutting, although this did not occur by the third entry on all of the plots in our simulation.

General comparisons of selection system and diameter-limit cutting

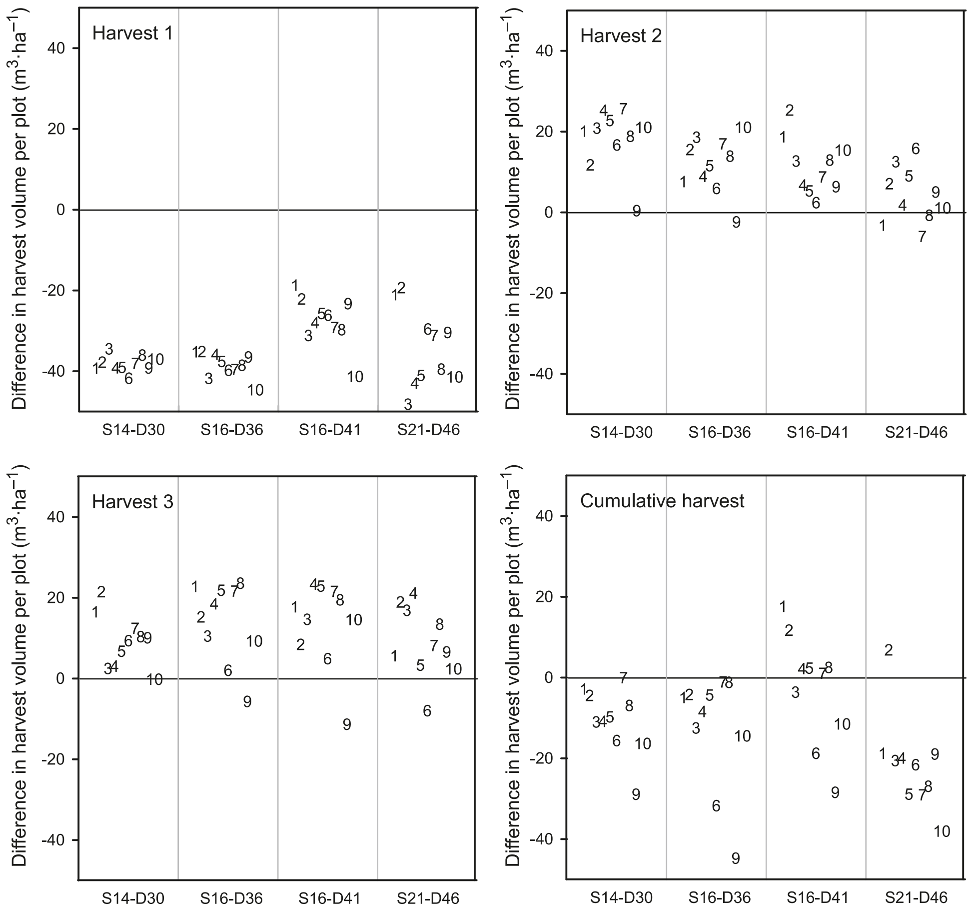
Although the production of sawtimber was not signifi-

Table 2. Coefficient of variation in total sawtimber harvest volumes across the 10 simulated plots.

	Coefficient of variation (%) by treatment						
Cutting period	D30	S14	D36	D41	S16	D46	S21
Harvest 1	9	14	11	14	16	24	21
Harvest 2	19	5	20	17	7	19	15
Harvest 3	8	3	18	20	5	30	12
Cumulative harvest	6	4	9	10	6	14	9

Note: Minimum cutting diameter for diameter-limit treatments: 30 cm DBH (D30), 36 cm DBH (D36), 41 cm DBH (D41), and 46 cm DBH (D46); residual basal area for selection system treatments: 14 $m^2 \cdot ha^{-1}$ (S14), 16 $m^2 \cdot ha^{-1}$ (S16), and 21 $m^2 \cdot ha^{-1}$ (S21).

Fig. 7. Within-plot comparisons of harvest volumes between selection system and diameter-limit cutting of similar intensity and cutting cycle length. Differences are positive if selection system treatment resulted in higher harvest volumes and otherwise negative. Minimum cutting diameter for diameter-limit treatments: 30 cm DBH (D30), 36 cm DBH (D36), 41 cm DBH (D41), and 46 cm DBH (D46); residual basal area for selection system treatments: 14 $m^2 \cdot ha^{-1}$ (S14), 16 $m^2 \cdot ha^{-1}$ (S16), and 21 $m^2 \cdot ha^{-1}$ (S21).



cantly different in all cases of our simulation, selection system on average yielded significantly greater harvest volumes at later entries, compensating for the initial advantage of diameter-limit cutting. Assessments in northern conifer (Sendak et al. 2003; Kenefic et al. 2005) and Appalachian hardwood stands (Miller and Smith 1991; Schuler 2004) have also shown that cumulative harvest volumes following repeated selection system cutting approached those of moderate to heavy diameter-limit cutting, even when sawtimber production rates were equivalent. In those stands, the lower harvest volumes from later diameter-limit treatments were due to the limited number of smaller trees growing past the threshold cutting diameter, which was also the case for most plots in our simulations.

The selection system silviculture simulated during our analysis maintained a greater proportion of the total volume in large sawtimber trees than did either moderate or heavy diameter-limit cutting. This result is also consistent with other reports (Kenefic et al. 2005; Nyland 2005) and is important to consider in forest types where size affects tree grade and value. Selection system has also resulted in higher economic returns due to the greater proportion of yield from larger and higher grade trees (Strong et al. 1995; Sendak et al. 2000; Leak and Sendak 2002; Kenefic et al. 2005). Earlier assessments by Nyland (2005) and Kenefic et al. (2005) have demonstrated this difference compared with diameter-limit cutting as well. And while Erickson et al. (1990) and Buongiorno et al. (2000) suggested that a 38–40 cm minimum threshold for diameter-limit cutting would yield more large-sized sawtimber trees than selection system, our results indicate that to obtain large sawtimber production comparable with that of selection system would require a diameter-limit cutting threshold of ≥46 cm.

Sensitivity of results to model assumptions

A model is necessarily a simplification of real-world processes. The most important simplifying assumptions that we made were the lack of species differences (all trees were represented as sugar maple), the absence of ingrowth, and the omission of tree mortality. These simplifications made it possible to focus on the sources of variation of greatest interest: the initial conditions represented by the stem maps, the cutting treatments, and the resulting effects on growth and yield. Here, we address the likely consequences for our results of the simplifying assumptions that we made in the model.

Growth and yield from our simulations best approximate stands dominated by sugar maple and other shade-tolerant species growing in productive, mesic site conditions. Sawtimber volumes from this simulation could differ from stands initiating with a larger component of shade-intolerant species such as white ash, black cherry, or yellow poplar, which would have faster growth rates into large sawtimber sizes, particularly with heavy cutting intensities. Although selection system tends to favor regeneration of shade-tolerant species, some studies also indicate that it maintains more shade-intolerant trees than diameter-limit cutting (Angers et al. 2005), and volume comparisons could differ over repeated entries with differential changes in composition.

Even though new trees (ingrowth) would not enter into our estimates of harvest volumes in the time frame of our simulations, omitting ingrowth means that competition with existing stems is underestimated. Preliminary tests indicated that accounting for the added basal area of new ingrowth, using stem densities reported by Hansen and Nyland (1987) for conditions similar to those following our simulated cuts, would reduce growth projections by only 0.02%–3% for light cutting and 4%–7% for heavy cutting. Even these projected differences may be overestimated, as most competition models weight basal area of smaller trees less than they weight trees with a size comparable to the subject tree (Biging and Dobbertin 1995). Any bias due to omitting ingrowth would apply similarly to all cutting treatments, and the relative differences across cutting strategies would not likely differ.

Mortality among sawtimber-sized trees is generally considered minimal where silviculture focuses the growth onto trees of good health and vigor, reduces crowding among trees of all size classes, and removes trees likely to die or decline before the next cutting. Measured mortality rates in managed, uneven-aged northern hardwood stands of central and upstate New York have been 0.05%–1% annually for sawtimber trees (Kiernan et al. 2009), with similar rates reported for stands in New England (Leak and Gove 2008). In northern hardwoods of Ontario, natural mortality rates following selection system remained similarly low, around 1.5%. Total mortality levels including stress or felling damage increased that value just slightly to 3%, although mostly for smaller trees (Caspersen 2006). Omitting mortality in our model could slightly overestimate harvest volumes following repeated selection system, and maybe more so in regions where mortality may be higher than reported in the previous studies. The important question is whether this bias is constant across cutting treatments, but without access to empirically derived mortality rates for diameter-limit cutting in northern hardwood stands, we could not make that judgment.

It seems possible that diameter-limit cutting could result in higher mortality than selection system cutting. Although it is possible that some ingrowth could have eventually been lost to mortality, which was not simulated here, the scenario resulting from our simulations is not entirely implausible given that sugar maple can often survive oppressed in the understory for as long as 80 years (Canham 1985). Crowding among untreated poles in the diameter-limit stands may reduce tree vigor, leading to greater mortality, as suggested by Roach (1974); however, the degree to which mortality increases in diameter-limit cut stands as compared with selection system is poorly known. Some studies have found little difference in natural mortality between selection system and diameter-limit cutting (Sendak et al. 2003; Kenefic et al. 2005). On the other hand, logging damage may be significantly higher in diameter-limit cut stands (Nyland et al. 1976; Fajvan et al. 2002), and such damage has been linked to higher likelihoods of mortality (Guillemette et al. 2008). So if mortality is higher in diameter-limit stands due to increased intertree competition or more logging damage to residual trees, our simulations overestimate volumes from those treatments more than with selection system and underestimate the differences between the two strategies. More sophisticated models would account for differential mortality rates due to both natural and anthropogenically induced mortality. Future comparisons of cutting practices should also include attention to other forest types and other treatments such as modified diameter-limit practices.

Conclusions

Our simulations show that effects of cutting treatments on sawtimber production can vary widely among stands with dissimilar structures. Differences between our findings and those from some past studies may reflect the added control that we gained by applying a range of cutting treatments to a common set of initial diameter distributions. In general, moderate to heavy diameter-limit cutting up to a 41 cm maximum diameter reduced total sawtimber yields by the second harvest. Added production in the selection system plots narrowed the difference in cumulative yields but did not fully compensate for the heavy initial diameter-limit volumes within the timeframe of our study. The amount of sawtimber available at the first entry into a stand, the maximum size of trees left after harvesting, and the numbers of trees that might grow to sawtimber status before the next entry all affect comparisons of long-term sawtimber production as well as the harvest volumes taken out with the different cutting treatments.

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