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The Effects of Stand Structure After Thinning on the Growth of an Allegheny Hardwood Stand

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ABSTRACT. A 50-year-old Allegheny hardwood stand in which the crown canopy had stratified into distinct species groups was thinned to 60% relative density leaving dramatically different stand structures and species composition. Treatments included combined thinning, thin from middle, thin from above, thin from below, and unthinned control. Individual tree growth was stimulated most by thinnings that created openings in the main crown canopy and still retained adequate numbers of the larger stems of the faster growing species. Thinning from below, which removed primarily noncommercial saplings and small poles of the shade-tolerant species, did not affect diameter growth of the larger stems. Total stand growth in basal area and volume was dramatically reduced by thinning from above, which removed nearly all of the larger stems and faster growing species. Treatments that reduced growing stock in the largest size classes, where most of the stand value is concentrated, had a detrimental effect on future timber values. Best individual tree growth, and best stand growth in basal area, cubic volume, board volume, and dollar value occurred in the combined thin treatment. Future yields after any thinning can be viewed as the net effect of reduction in the amount of growing-stock capital and increases in residual tree growth resulting from reduced competition. Recommendations for appropriate types of thinning and timing of the first thinning in stands such as this are provided. FOR. SCI. 37(4):1182–1200.
ADDITIONAL KEY WORDS: Size-class distribution, species composition, cherry-maple type, increment.

THINNING IS THE MOST WIDELY RECOMMENDED CULTURAL PRACTICE in even-aged stands of eastern hardwoods. Thinning provides intermediate yields and permits salvage of volume that would otherwise be lost when trees die from overcrowding. The reduction in density brought about by thinning provides more space for the residual trees, thereby increasing their growth. Thinning also provides the opportunity to remove poorer quality stems, thus concentrating the growth on the most valuable trees in the stand. These effects, especially the growth responses from reduced stand density, have been well documented (Allen and Marquis 1980, Beck and Della-Bianca 1975, Braathe 1957, Dale 1980, Erdmann et al. 1985, Hilt 1979, Lamson 1985, Marquis 1969, Marquis 1986, Solomon 1977).

However, much of our knowledge on thinning still comes from forest types that are relatively easy to study—even-aged stands of a single species, often conifers, and sometimes in uniformly spaced plantations. Many stands of eastern hardwoods contain a mixture of species that spans the full range of growth rates and

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shade tolerance. Such stands have extremely complex structure and composition, making the traditional theories on thinning difficult to apply.

These mixed, even-aged hardwood stands often have a canopy that is stratified by species, with fast-growing intolerants in the dominant positions, and slower growing shade tolerants beneath. Dense stands may have a substantial number of shade-tolerant saplings the same age as the larger trees, giving the stand an inverse J-shaped diameter distribution usually associated with an all-age condition or with very young even-aged stands.

In these young mixed species stands, suppressed trees of the shade-tolerant species have the capacity to respond to release (Hough and Taylor 1946). This is in contrast to some other forest types, where lower crown class trees of less tolerant species do not respond (Oliver and Murray 1983). In the Allegheny hardwoods, it is biologically possible to thin in markedly different ways, favoring the species and size groups of either upper or lower crown strata.

If thinning is done primarily from below in such stands, noncommercial saplings would be removed which have questionable impact on the growth of the crop trees. On the other hand, if thinning occurs primarily from above, the faster growing, more valuable species, are removed, leaving the site dominated by the less valuable species and slower growing individuals. We do not know whether the noncommercial saplings can be ignored, and we need a more complete understanding of how stand structure and species composition interact with stand density in determining growth responses in such stands.

This paper reports on growth response from a thinning experiment in a mixed hardwood stand where density was reduced to a standard level, but the method of thinning was varied to concentrate cutting in different size classes. These thinnings altered stand structure and species composition in dramatically different ways.

METHODS

Stand and Site Characteristics

Thinning plots were established in a pole-size, even-aged cherry-maple stand on the Allegheny Plateau of northwestern Pennsylvania. Primary species in the stand include: black cherry (*Prunus serotina* Ehrh.—a fast-growing, high value, shade-intolerant species); red maple (*Acer rubrum* L.—a moderately fast-growing, medium value species of intermediate shade tolerance); sugar maple (*Acer saccharum* Marsh.—a slow-growing, medium value, shade-tolerant species); and American beech (*Fagus grandifolia* Ehrh.—a slow-growing, low value, shade-tolerant species). Sweet birch (*Betula lenta* L.), yellow birch (*Betula allegheniensis* Britton), yellow-poplar (*Liriodendron tulipifera* L.), cucumbertree (*Magnolia acuminata* L.), pin cherry (*Prunus pensylvanica* L.), and striped maple (*Acer pensylvanicum* L.) occurred as minor components.

This cherry-maple stand originated in 1922–23 following the clearcutting of the original old-growth stand. Although there were a few small-diameter residuals left from the original stand, the clearcutting was very complete, removing most trees down to 2 or 3 in (5 to 8 cm) diameter at breast height (dbh). Larger trees were harvested for sawtimber, and smaller trees were converted into charcoal or wood chemicals. Thus, the present stand is even-aged for all practical purposes. At the time of thinning in 1975 and 1976, the stand was 53–54 years old and fully stocked, with basal area of 130 to 140 ft^2/ac (30 to 32 m^2/ha). Median stand diameter (diameter at the midpoint of the basal area distribution) was about 9 in. (23 cm), but individual trees as large as 23 in. dbh (58 cm) were present. These large trees are cherry, all of which originated after the 1922–23 clearcut. Total cubic volumes were about 2,000 ft^3/ac (140 m^3/ha), and sawlog volumes were 3,000 to 4,000 bf/ac International ¼″ log scale (35 to 45 m^3/ha) (Table 1).

At the time of thinning, black cherry represented 30 to 40% of the basal area, while sugar maple and beech accounted for 30 to 65%. Most of the remainder was red maple. Sugar maple and beech represented 80 to 90% of the 800 to 900 trees/ac (2,000–2,200 trees/ha), but these shade-tolerant species were concen-

TABLE 1.

Actual stand characteristics before and after treatment.

	RD	BA	NT	QSD	MD	% BC	% RM	% SM-AB	SAP BA	CV	BV	$
Control												
Initial	99	126	842	5.2	8.8	34	10	46	29	19.7	2.9	810
Combined												
Initial	103	138	964	5.1	8.7	43	24	30	30	22.1	2.9	924
Cut	41	52	566						18	6.8	1.0	286
Residual	62	86	398	6.3	9.3	42	26	28	12	15.3	1.9	638
Middle												
Initial	106	148	933	5.4	9.5	43	8	31	30	25.1	4.4	1,437
Cut	44	67	311						7	12.6	2.2	754
Residual	62	81	622	4.9	9.0	36	10	41	23	12.5	2.2	683
Above												
Initial	108	132	771	5.6	9.3	32	1	63	30	21.0	3.6	1,410
Cut	44	66	219						4	14.3	3.2	1,311
Residual	64	66	552	4.7	6.5	15	1	84	26	6.7	0.4	99
Below												
Initial	102	132	910	5.2	9.5	36	7	49	33	21.4	4.1	1,575
Cut	39	36	671						26	1.6	0.3	150
Residual	63	96	239	8.6	11.2	48	8	33	7	19.8	3.8	1,425

RD = Relative density or stocking as defined by Roach (1977), in percent.
BA = Basal area in trees 1.0″ dbh and larger, in ft^2/ac.
NT = Numbers of trees/ac.
QSD = Quadratic stand diameter.
MD = Median diameter (midpoint of basal area distribution) as defined by Marquis et al. (1984).
%BC = Percentage of total stand basal area in black cherry.
%RM = Percentage of total stand basal area in red maple.
%SM-AB = Percentage of total stand basal area in sugar maple and American beech.
SAP BA = Basal area in sapling-size trees (1–5″ dbh) in ft^2/ac.
CV = Cubic volume in trees 6″ dbh and larger to inside diameter of 4.5″ in cords/ac.
BV = Sawtimber volume in trees 12″ dbh and larger to inside diameter of 10.5″, International ¼″ Rule, in mbf/ac.
$ = Value, in dollars/ac.

trated in the smaller diameters and lower crown classes. Many were less than 4 in. (10 cm) dbh. Black cherry stems, although relatively few in number, made up the majority of the larger diameters and dominated the main crown canopy. Red maple was intermediate. This highly stratified, inverse J-shaped diameter distribution (Figure 1) is common in even-aged Allegheny hardwoods and makes the manipulation of stand structure a major consideration in any partial cutting.

This stand is located on the relatively flat, unglaciated Allegheny Plateau at an elevation of 2,000 ft (610 m). Soils are stony, sand loams that are developed from sandstone and shale parent materials. A fragipan that impedes soil drainage occurs within 1 ft (30 cm) of the surface in a few spots, but the majority of the area is well drained to moderately well drained. Rainfall in the area averages 42 in. (106 cm) annually and is well distributed throughout the year. Average July temperature is 66°F (19°C), and the average growing season is 123 days.

Experimental Methods

This study is part of a much larger thinning experiment in Allegheny hardwoods. The larger study includes stands of other ages and species, and includes treat-

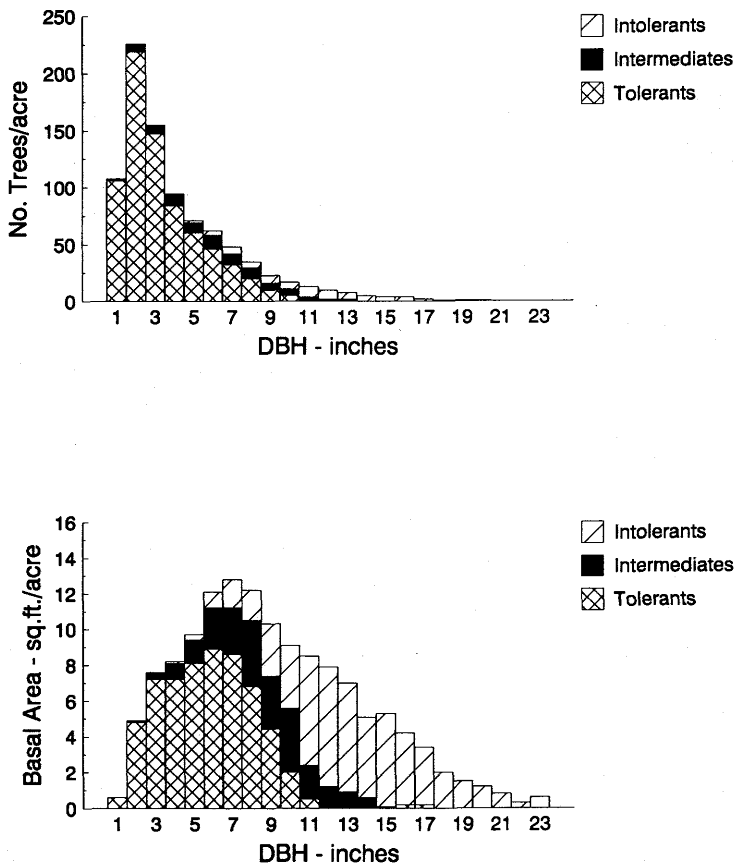

FIGURE 1. Diameter distribution of a 50-year-old cherry-maple stand prior to thinning.

ments to evaluate the effect of stand density on growth and yield. The data presented here are from 15 plots representing three replicates each of five treatments to evaluate the effects of stand structure on growth and yield. Each plot is 2 ac (0.8 ha) overall, and rectangular in shape. The central 0.6-ac (0.24 ha) portion of each plot was the measurement area, and every tree 1.0 in (2.5 cm) dbh and larger in this area was numbered and marked at breast height so that repeated diameter measurements could be taken at the same point on the bole. The remaining 1.4 ac (0.57 ha) surrounding the measurement plot was an isolation strip [generally 66 ft (17 m) wide]. The isolation strip received the same treatment as the interior measured plot.

All plots that were cut were reduced to between 60 and 70% relative density. Relative density is an index to the degree of crowding in a stand. The relative density measure used throughout this paper (Roach 1977, Stout and Nyland 1986) is based on empirical studies that define the average maximum density (in basal area) of undisturbed stands of given species composition and average tree size (diameter). The actual basal area of any given stand is then expressed as a percentage of the average maximum density for that type of stand. Since basal area varies widely depending on stand diameter and species composition, relative density provides a more useful index to crowding than absolute basal area.

The thinnings were designed to alter stand structure as follows:

A. Control—No thinning.
B. Combined thinning—A combination of commercial thinning in the merchantable size classes, plus noncommercial thinning in the sapling-size class. This is the standard type of thinning recommended in young Allegheny hardwood stands that contain a high basal area in sapling-size stems and is more completely defined in Marquis et al. (1984). Openings were created in the main canopy, and the basal area in noncommercial sizes was reduced appreciably as well. The overall effect was a slight increase in stand diameter, and little change in the shape of the diameter distribution curve. This thinning generally favored the larger trees, most of which are the intolerant species.
C. Thin from middle—A commercial thinning was made in the merchantable size classes much as in the combined thinning, but no noncommercial saplings were cut. Instead, additional material was removed from the merchantable sizes to provide the same residual relative density. This treatment reduced average stand diameter and left a much higher proportion of the growing space occupied by sapling-size trees. The pole class, which represented the bulk of the basal area before cutting, was drastically reduced, and removals in the sawtimber sizes were also higher than in the combined thinning. Diameters were altered toward a bi-model distribution. Species composition shifted toward the shade-tolerant species.
D. Thin from above—A commercial thinning was made by cutting on a diameter basis, removing the largest sizes first and working down until the desired residual density was achieved. This cutting dramatically reduced average stand diameter, removed nearly all of the sawtimber-size trees, and left a residual of primarily sapling-size and pole-size stems of the shade-tolerant species. The original inverse-J diameter distribution was truncated in the large diameters.
E. Thin from below—A noncommercial thinning was applied by cutting on a diameter basis, removing the smallest sizes first, and working up until the desired residual relative density was achieved. This cutting dramatically increased average diameter, virtually eliminated the sapling class, and left the residual stand dominated by the larger trees of the intolerant and intermediate species. The diameter distribution was changed toward a bell-shaped curve.

Each plot was marked for thinning by dividing it into smaller subplots of 0.1 ac (0.04 ha) each and marking each subplot to the desired density and structure. This helped to ensure uniformity of treatment across the plot area. Structure goals dominated the marking, especially in the thin-from-below and thin-from-above treatments. But when there were opportunities to choose between several trees of the same size class, poorer quality, less vigorous trees of the lower value species were removed.

Thinning in the merchantable sizes was accomplished by a commercial timber sale contract, though the volumes and values removed were economically marginal on some plots. Noncommercial thinning was done by technicians after commercial cutting was complete. Logging activity—felling and skidding—resulted in destruction of some residual trees. Nearly all such damage occurred in the sapling class. The amount of damage was typical of that experienced in commercial logging of such stands; this damage accounts for the loss of some saplings in those treatments where sapling removal was not prescribed.

Additional data on each thinning treatment are summarized in Table 1, Table 2, and Figure 2. Although all treatments were cut to the same relative density as defined by the Allegheny hardwood stocking chart (Roach 1977), note that densities as expressed by actual basal area and volume differed among treatments. Studies elsewhere have demonstrated that the various density indices are not equivalent in their characterization of intensity of cut nor in correlation with subsequent growth (Larson and Cameron 1986, Oliver and Murray 1983). Such differences are especially pronounced when thinning alters stand structure, as in this experiment. Even with this recognized shortcoming, the stocking measure used to control thinning here is the best available; it accounts for tree size and species composition and therefore provides a better measure of stand crowding than absolute basal area or volume.

Diameter measurements of all trees on the plots were made prior to thinning, immediately following thinning, and three or four additional times since thinning. The 15 plots included here are part of two different blocks in the larger study; although all are located in the same stand, the two blocks were established 1 year apart. Data presented here cover growth over a 10-year span. In all, there were nearly 7,800 individually numbered trees in this study.

Statistical comparisons were made among stand growth parameters (in basal area and volume) using analysis of variance for a completely randomized design. Individual comparisons were made using t-tests for nonpaired observations. Simple linear regressions were calculated for each treatment relating individual tree diameter growth to initial dbh. Slopes and intercepts of the five resulting lines were tested for differences using procedures described by Dixon and Massey (1957). In all tests, an alpha significance level of 0.05 was used.

Even though all plots in this study were in the same reasonably uniform stand, there were important differences among treatments in such initial stand parameters as volumes, values, and numbers of trees in each dbh class in the important sawtimber sizes. For example, the thin-from-middle treatment removed 43% of the sawtimber while the combined thinning removed only 31%. But because the thin-from-middle plots had considerably more sawtimber initially, the residual stands of this treatment still had more sawtimber after cutting than the combined-thin plots where the sawtimber cut had been lower. This variability confounds comparisons among treatments.

Therefore, we adjusted the initial stand conditions in each plot to provide

TABLE 2.

Adjusted stand conditions before and after treatment.

	RD	BA	NT	QSD	MD	% BC	% RM	% SM-AB	SAP BA	CV	BV	$
Control												
Initial	105	136	887	5.3	9.2	38	10	44	31	22.1	3.6	1,259
Combined												
Initial	105	136	887	5.3	9.2	38	10	44	31	22.1	3.6	1,259
Cut	43	48	508						18	5.9	0.6	179
Residual	62	88	379	6.5	10.2	45	10	36	13	16.2	3.0	1,080
Middle												
Initial	105	136	887	5.3	9.2	38	10	44	31	22.1	3.6	1,259
Cut	43	48	508						10	10.2	1.5	515
Residual	60	77	588	4.9	9.0	37	9	45	21	11.9	2.1	744
Above												
Initial	105	136	887	5.3	9.2	38	10	44	31	22.1	3.6	1,259
Cut	44	68	291						8	13.7	2.9	1,087
Residual	61	68	596	4.6	7.2	23	11	58	23	8.4	0.7	172
Below												
Initial	105	136	887	5.3	9.2	38	10	44	31	22.1	3.6	1,259
Cut	39	36	636						25	1.8	0.0	8
Residual	66	100	251	8.5	10.8	49	10	30	6	20.3	3.6	1,251

RD = Relative density or stocking as defined by Roach (1977), in percent.
BA = Basal area in trees 1.0" dbh and larger, in ft^2/ac.
NT = Numbers of trees/ac.
QSD = Quadratic stand diameter.
MD = Median diameter (midpoint of basal area distribution) as defined by Marquis et al. (1984).
%BC = Percentage of total stand basal area in black cherry.
%RM = Percentage of total stand basal area in red maple.
%SM-AB = Percentage of total stand basal area in sugar maple and American beech.
SAP BA = Basal area in sapling-size trees (1–5" dbh) in ft^2/ac.
CV = Cubic volume in trees 6" dbh and larger to inside diameter of 4.5", in cords/ac.
BV = Sawtimber volume in trees 12" dbh and larger to inside diameter of 10.5", International ¼" Rule, in mbf/ac.
$ = Value, in dollars/ac.

growth and yield comparisons based on identical initial plot parameters. This procedure is similar to an analysis of covariance.

The starting point for all treatments was a grand average stand created from all 15 plots before cutting. Data on this average initial stand are presented in Figure 1 and Table 2.

Residual stands after each of the thinning treatments were derived by removing trees from the average initial stand in the same proportions as each treatment removed trees from the actual plots. Thus, if the thinning from the middle removed 35% of the 12 in. dbh trees from the actual plots (for example), we removed 35% of the 12 in. trees from the average stand in calculating the adjusted residual for that treatment.

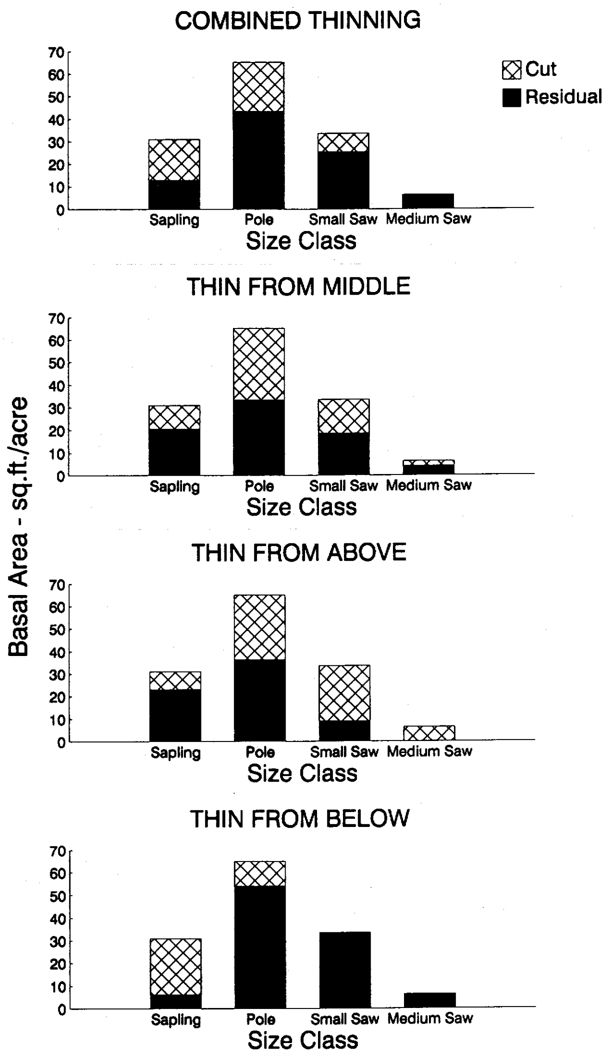

FIGURE 2. Distribution of cut by size class.

In making these calculations, data from all three actual plots were averaged by 1 in. (2.54 cm) dbh classes. These raw averages were plotted and smoothed using the distance weighted least squares smoothing function in the computer program SYGRAPH (Wilkinson 1988). Values were then interpolated from the smoothed line for use in the calculations. Since species composition did not differ importantly within dbh classes, removals were made across all species.

In a similar manner, mortality percentages and average growth rates were calculated for each treatment by dbh classes, and the smoothed values were applied to the average stand as described above. Thus, adjusted stands for each treatment were calculated from an identical starting point, using average amounts of cutting, average mortality, and average growth observed in the actual treatments.

These calculations assume that the growth response on the adjusted stands will be identical to those observed in the same diameter classes in the actual stands. This assumption seems reasonable, since the initial and residual stands were not markedly changed by the adjustments. The extent of the adjustments to initial starting conditions may be evaluated by comparing Table 1 (actual data) with Table 2 (adjusted data). The yields thus calculated do not change the conclusions drawn from the actual data, but they do show the differences among treatments more clearly. In this paper, significant differences ascribed to treatments are based on statistical tests of the actual data, even though all bar charts were drafted using adjusted stand data.

RESULTS

Individual Tree Growth

As expected, diameter growth of individual trees was highly correlated with initial dbh (Figure 3). The larger trees, which are those in the upper crown classes with the best competitive position, grew faster than the smaller trees. The larger trees also were the intolerant species, such as black cherry, which have achieved their dominant positions because they have grown faster throughout the life of the stand. All regressions were highly significant (well beyond the 0.01 level), and had

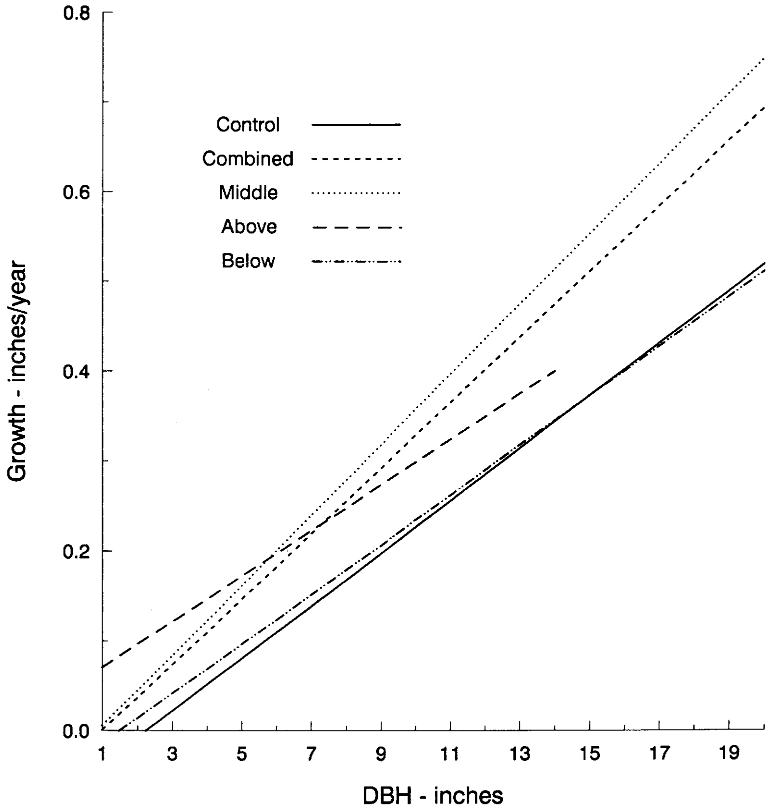

FIGURE 3. Diameter growth, all species combined.

coefficients of determination (r^2) of 0.88 to 0.96 for all except the thin from above treatment, for which r^2 was 0.59.

Tests among the five regressions representing the five treatments (Figure 3) revealed three significantly different groups of equations: (a) the control and thin from below, (b) the combined thin and thin from middle, and (c) the thin from above. The equations for each group were significantly different from the other two, but equations within a group did not differ.

The two thinnings that provided for opening of the main crown canopy while still retaining some of the larger cherry and red maple (combined thin and thin from the middle) resulted in an important increase in diameter growth of the residuals. Even the dominant and codominant trees responded, in comparison with trees of the same size and species from unthinned plots. In contrast, thinning from below, which did not provide for important opening of the main canopy, provided no stimulation of diameter growth. This is true even though the relative densities were the same as in the other thinnings, and the thin-from-below plots have a park-like appearance due to removal of nearly 75% of the total number of trees.

Diameter growth response of the smaller shade tolerant trees left after thinning from above was dramatic because of the extreme opening of the main canopy. Most of these small residuals, which were formerly in the intermediate or suppressed crown classes, were thrust into codominant or dominant crown positions by this severe treatment. The slope of the diameter growth curve for this treatment (Figure 3) is less than that for the other four treatments because of the dramatic increase in growth of these small residual trees. Although their relative increase in diameter growth was great, it was not enough to match the rates of the larger cherry and red maple that had been removed.

Stand Growth

Net growth, survivor growth, ingrowth, and mortality for the five treatments are presented in Table 3, in terms of basal area, cubic volume, board-foot volume, and value. The differences in growth and mortality between these various expressions are due largely to differences in the minimum dbh of trees included. Basal area includes trees 1 in. and larger, cubic volume includes trees 6 in. and larger, board foot volume includes trees 12 in. and larger.

Net Growth

Net stand growth in basal area, cubic volume, board volume, and value was greatest in the combined thin treatment. Since net stand growth represents the net effect of survivor growth, ingrowth, and mortality, results will be explained in terms of these individual growth components.

Mortality

Basal area mortality was highest in the control and next highest in the thin-from-above treatment. It was low in the other thin treatments. Nearly all of the trees that died were suppressed shade tolerants in the sapling class. The fact that mortality was concentrated in the sapling size class is reflected in very low cubic-foot and board-foot mortality.

High basal area mortality among the suppressed trees in the control stand is the normal mortality expected from crowding in fully stocked stands such as this, where basal area and stand diameter are increasing regularly. Thinning reduced

TABLE 3.

Annual stand growth after treatment for adjusted stands.

Treatment	Basal area (ft^2/ac)	Cubic volume (ft^3/ac)	Board volume (mbf/ac)	Value ($/ac)
Control				
Net	0.70	61.35	292.80	51.34
Survivor	2.62	58.90	258.60	50.52
Ingrowth	0.01	2.60	43.70	3.12
Mortality	1.93	0.15	9.50	2.30
Combined Thin				
Net	2.86	72.68	402.20	110.01
Survivor	3.14	69.40	324.60	65.37
Ingrowth	0.02	3.30	77.60	44.64
Mortality	0.30	0.02	0.00	0.00
Thin from Middle				
Net	2.57	61.39	253.10	53.20
Survivor	2.86	54.60	217.20	40.75
Ingrowth	0.03	6.80	35.09	12.45
Mortality	0.32	0.01	0.00	0.00
Thin from Above				
Net	1.04	42.33	135.50	30.66
Survivor	2.00	35.60	102.70	17.71
Ingrowth	0.07	6.80	33.80	13.25
Mortality	1.03	0.07	0.09	0.30
Thin from Below				
Net	2.19	58.25	309.10	54.83
Survivor	2.52	56.90	262.70	49.50
Ingrowth	0.02	1.40	47.80	5.63
Mortality	0.35	0.05	1.40	0.30

mortality by providing more growing space, so that crowding was no longer a major factor. Even in the thinned plots, the few trees that died were in the smallest, most suppressed classes—apparently trees that were already so weakened by years of suppression that they were unable to respond to the better growing conditions after thinning.

In the thin-from-above treatment, a high proportion of the residuals were these long-suppressed and weakened individuals, which were drastically exposed by the near complete removal of the larger trees. As a result, mortality in this treatment was significantly higher than in any of the other thinnings, and nearly as high as in the control. In fact, net growth on the thin-from-above treatment was actually negative for the first few years after thinning—when mortality was occurring rapidly and before the better of the surviving residuals had a chance to expand their crowns and respond with increased growth.

Ingrowth

Ingrowth in basal area was negligible in all treatments. There were very few trees below the 1.0 in. (2.54 cm) threshold diameter prior to thinning, and therefore few trees to cross the threshold during the 10-year span of this study.

However, ingrowth into size classes that qualify for cubic volume or board-foot volume was important in all treatments. Ingrowth into sawtimber was about 20% of total sawlog volume increase. This is to be expected in stands of this age and size arrangement, since many trees are just below the sawtimber threshold.

Treatments that seriously reduced the growing stock in the pole class just below the sawtimber threshold, such as the thin-from-middle treatment, had less sawtimber ingrowth than those that preserved adequate pole growing stock. Ingrowth into sawtimber was also low on the two treatments that did not open the main crown canopy enough to stimulate growth on the pole-size trees (control and thin-from-below treatments). Ingrowth into sawtimber in the combined thinning was nearly twice that on any of the other treatments.

Survivor Growth

Survivor trees are trees present after thinning at the beginning of the study and still alive after 10 years. Survivor growth does not include either ingrowth or mortality. Therefore, survivor cubic volume growth and board foot volume growth is volume increment on trees already beyond the threshold diameter at the beginning of the study.

The amount of stand growth that occurs on survivor trees after a thinning is a function of two opposing factors: the amount of growing stock left (the capital on which growth can accumulate), and the amount of stimulation of growth resulting from reduced crowding. Thinning will reduce the amount of growing stock or capital, and this tends to lower total survivor growth. But the thinning also reduces crowding, so the smaller number of residuals are stimulated to grow faster, and this tends to increase total survivor growth.

These opposing effects are illustrated in Figure 4 for basal area survivor growth and board volume survivor growth. The solid portion of each bar is the growth that would have been made by the smaller number of residual trees (the capital) had they continued to grow at the same rate as before thinning (the control rate). As compared to the controls, the reduced heights of the solid bars in the thinning treatments are the result of fewer trees (less capital). The total height of each bar is the total survivor growth, so the cross-hatched portion is the amount that growth of the residuals was stimulated by thinning.

Note that total survivor growth in both basal area and board volume was slightly higher on the combined thinning than on the control. The faster growth on the thinned residuals offsets the fact that there were fewer of them. Since cutting occurred in all size classes, there were sufficient numbers of sawtimber trees to maintain high board volume growth. Ingrowth into sawtimber was also large in the combined thin due to substantial number of trees in the pole size class. Thus, net board volume growth in this treatment was much greater than in any of the other treatments (Table 3).

On the thin-from-middle treatment, the reduced number of trees was also stimulated to grow faster, but the increased growth was enough to compensate for the reduction in numbers of trees only for basal area growth and not for board volume growth (Figure 4). All of the trees removed came from the pole- and sawtimber-size classes, so most of the growth increase occurred on residual sapling-size trees that did not contribute to board volume. Ingrowth into sawtimber was also low in this treatment due to the reduced number of trees in the pole

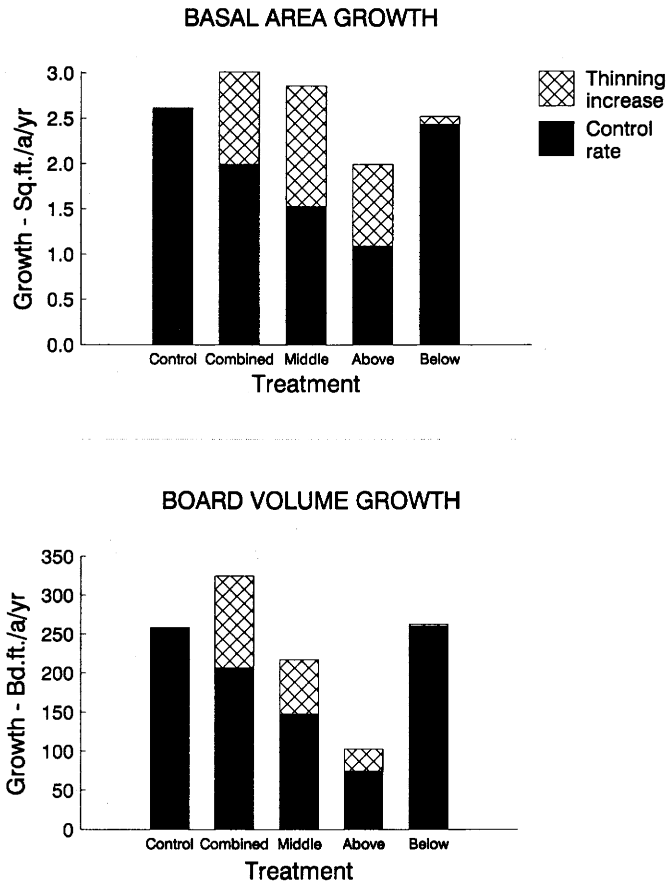

FIGURE 4. Survivor growth by treatment, partitioned into two parts: (a) growth if all survivors continue to grow at the same rate as the controls, and (b) growth increase due to thinning.

size class, so net board volume growth was lower than all other treatments except the thin-from-above (Table 3).

On the thin-from-below treatment, there was very little reduction in capital and very little stimulation of growth (Figure 4). This is especially clear in board volume, where very few sawtimber trees were removed, and the lack of opening in the main canopy produced no measurable increase in board volume growth rate. So the net effect is again no significant change in total survivor growth as compared to the control.

On the thin-from-above treatment, there was a large reduction in capital, and a considerable increase in basal area growth of the residual. However, in this extreme treatment, the increased growth was not enough to offset the drastic reduction in capital, especially in board volume growth, where the few sawtimber-sized residuals produced only about one-third as much growth as the control or the better thinning treatments.

However, with the exception of extreme treatments such as the thin from above, the data in Figure 4 illustrate the fact that most thinnings do not significantly affect total stand survivor growth. Instead, thinnings redistribute approximately the same amounts of growth over a smaller number of faster growing trees.

When stand structure is altered by thinning, stand growth is not only redistributed to a smaller number of trees, it is also redistributed to trees of different size, species, and value. Figure 5 illustrates these changes.

The bar charts in Figure 5 are identical to those for basal area in Figure 4, except that each stand is further subdivided into three major size classes. In the control stand, the sawtimber-size class represents the largest 50 trees/ac (125/ha); the poletimber-size class corresponds approximately to the next largest 150 trees/ac (370/ha); and the sapling class includes all the remaining small trees (650/ac or 1,600/ha). It should be remembered that most of the value in these

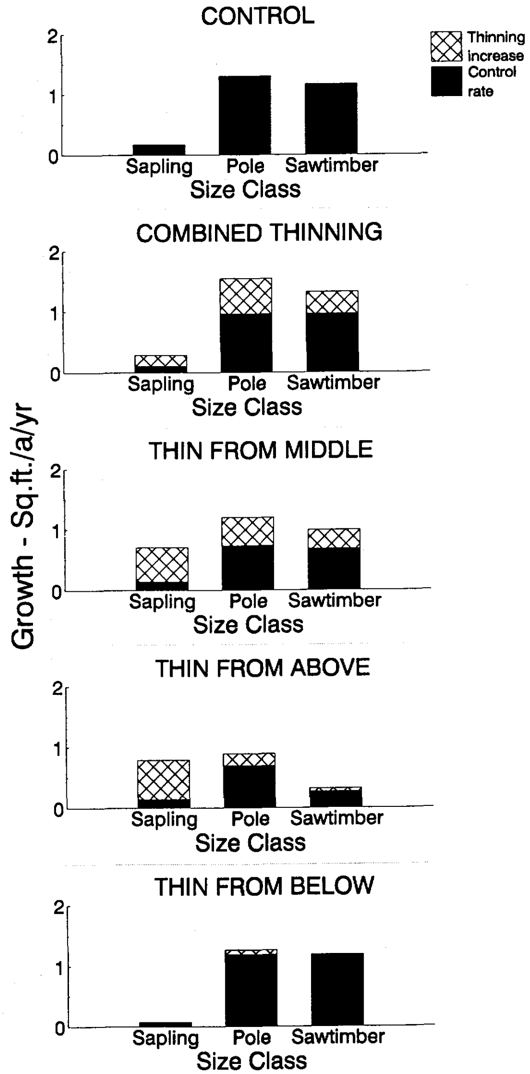

FIGURE 5. Survivor basal area growth by treatment and size class, partitioned into two parts: (a) growth if all survivors continue to grow at the same rate as controls, and (b) growth increase due to thinning.

stands is concentrated in the sawtimber trees that are dominated by the shade-intolerant black cherry. About 93% of the value in the control stand was contained in just 50 sawtimber trees at the start of the experiment.

In the control treatment, these 50 largest trees/ac produced nearly as much survivor basal area growth as the remaining 800 trees/ac. The 150 next largest trees/ac (poles) contributed most of the remaining survivor growth. The large number of sapling-size trees had little effect on total stand survivor growth. In addition, most of the mortality occurred in the sapling size class, so net basal area growth in the sapling class was negative in the control plots.

It is apparent that almost half of the total basal area growth and nearly all of the value is concentrated in a small proportion of the largest stems in the control stand. Treatments that reduce growing stock in the largest size class therefore will have a much greater impact on future timber production than those that produce similar reductions in smaller size classes, and vice versa.

In Figure 5, note how thinning from below has minimized basal area growth in the sapling class and redistributed it to the pole and sawtimber classes. Although the amount of growth redistributed was very small, the net effect of this treatment is to concentrate growth on sawtimber-size trees and minimize growth that would normally be placed on sapling-sized trees that will not grow large enough to yield high-value products in the usual rotation period.

In contrast, the thin-from-above treatment shifted most of the stand growth to those low-value saplings and seriously reduced growth in the two larger classes—especially in the sawtimber class. The overall reduction in growth, coupled with this redistribution of growth to the slow-growing, shade-tolerant sapling class, will drastically limit the yield of high-value products in the future.

The thin-from-middle treatment also results in redistribution of a substantial proportion of stand growth in basal area to the low-value sapling class. Survivor growth in the pole and sawtimber classes is about the same as in the control, but less than in the combined thin. Residual stocking in poles is substantially reduced in this treatment (compared to both the control and combined thin—Figure 2), and lack of ingrowth into sawtimber from the pole class reduced net sawtimber growth substantially compared to the combined thin. Lack of sawtimber ingrowth will probably continue to reduce high-value yields from this treatment over the long term.

The combined thinning redistributed growth to a smaller number of trees, but did not cause a major shift in growth among size classes. However, there was an important increase in growth of the pole and sawtimber classes. Value yields from this treatment promise to be better than those from the control and thin-from-below treatment, primarily because growth has been concentrated on the best quality pole and sawtimber trees. Future value yields should be noticeably better than the thin-from-the-middle treatment and dramatically better than the thin-from-above treatment. Since the thin-from-the-middle and thin-from-above treatments provided substantially greater yields from the initial cut, it is important to look at thinning yields and subsequent growth combined. On this basis, the combined thinning provided the greatest total yield of all treatments, and the thin-from-above provided the lowest yield (Table 4). We expect these differences to become more pronounced with additional time.

It is clear that stand growth is strongly influenced by the relatively small number of trees that constitute the biggest stems in the stand. Best volume

TABLE 4.

Total value yields by treatment for 10-year study period.

Treatment	Cutting yield	Residual value	Value increase	Total yield
	($/ac)			
Control	—	1259	513	1772
Combined	179	1080	1100	2359
Middle	515	744	532	1791
Above	1087	172	307	1566
Below	8	1251	548	1807

growth will occur after thinnings that strike a balance between retaining maximum numbers of these largest trees while still providing sufficient cutting in the main crown canopy to stimulate growth rate of the residuals. Cuttings that do not extend into the main canopy do not stimulate residual tree growth. Cuttings that remove substantial portions of the larger merchantable trees provide for large increases in residual growth rate. But the increased growth on those small residuals does not equal the inherently fast growth of the larger shade-intolerant species removed, and a high proportion of total stand growth is put on trees that will not reach sawtimber size during the usual rotation, so value yields over the rotation may be substantially reduced. Oliver and Murray (1983) found similar results with Douglas-fir, where the larger trees in the stand provided a major share of stand growth, and where growth after thinning was as much a function of stand structure as of density.

NONCOMMERCIAL SAPLINGS—TO TREAT OR NOT?

One of the major reasons for installing this study was to determine whether the noncommercial saplings could be ignored in thinnings. In older stands, there are relatively few of them and it is intuitively clear that they have little impact. But in these stratified mixed-species stands that are just reaching the age when commercial thinning is feasible, the saplings often represent a substantial part of the stand. In this study stand, they represented over 75% of the trees and nearly 25% of the basal area (Figure 1).

Because the saplings are well below the main crown canopy, most foresters believe that they have little impact on the growth of the dominants and codominants, even though they are numerous. This study supports that belief—removal of nearly all the saplings in the thin-from-below treatment did not stimulate the growth of the larger residuals significantly.

But it does not necessarily follow that these saplings can be ignored. Even though their removal does not affect the growth of the dominants and codominants, ignoring them and cutting heavily in the merchantable sizes can leave a residual stand dominated by small, poor vigor trees of the slower growing species. There will be relatively few good growing stock trees on which to add future value.

Where some of the saplings can be removed at no cost (for firewood, for example), the combined thinning appears to be the preferred alternative. But, if there is no market for sapling-size trees, and an investment is required to remove them, the return on that investment will probably not justify the expense. In this case, the alternatives are to attempt a commercial thinning in the merchantable size classes and ignore the saplings (the thin-from-middle treatment in this experiment), or to delay thinning for an additional 10 years or so, until mortality from crowding has reduced the sapling component to a less important level.

In young stands such as this, which contain substantial stocking in the sapling size class, we believe that simply delaying the first thinning is the best choice. The short delay required by waiting should have little impact on yields over the full rotation. In addition, volumes cut in the combined thin were marginal for a commercial operation. The total value realized after just 10 years from the thin-from-the-middle treatment was not different from the control, and the lower sawtimber growth projected for this treatment suggests that the combined thin delayed for 10 years will provide considerably greater value over the full rotation (Table 4 and Figure 4).

In the thin-from-the-middle treatment of this experiment, 31% of the basal area and 45% of the relative density was left in sapling-size trees that will not reach sawtimber size during a normal even-age rotation. Sawtimber growth in the thin-from-the-middle treatment was reduced relative to the control, and reductions in the poletimber size class in this treatment minimized sawtimber ingrowth and promise to limit it even more in the future (Table 3). Based on these trends, we expect this treatment to have lower yields over the full rotation than the control, even though these two did not differ in total yield or value growth over the first 10-year period (Table 4). Therefore, this treatment is not recommended in stands that contain a large tolerant sapling component. The thin-from-above treatment clearly illustrates the severe loss in yield that can occur if cutting in the merchantable sizes is increased so much as to leave predominantly the smaller trees.

Another possibility, not tested here, is that a thin-from-the-middle treatment that left 75–80% stocking rather than the heavier cutting to 60% residual used here, might provide the desired early yield without depleting the growing stock in pole and sawtimber sizes. Of course, a lighter cutting would yield less income now and provide less growth stimulation. Without data on such a possibility, we prefer not to recommend it at this time.

Although it may not be feasible to invest in removal of noncommercial stems, their presence will sometimes make it desirable to postpone the first thinning in young stands until natural mortality reduces the sapling component. This effect is greatest in young highly stratified mixed stands where the saplings are shade-tolerate species, such as the stand studied here. In some computer simulation experiments conducted separately (Marquis 1986), it was found that rotation yields were maximized by delaying commercial thinning until the basal area in saplings dropped below about 20 ft^2/ac. At that time, commercial thinnings that do not include cutting of saplings become feasible.

CONCLUSIONS

Thinning prescriptions in hardwood stands often concentrate on regulation of residual stand density, with little or no attention to stand structure. In this experiment, all thinning plots were reduced to the same residual relative density (range between 60 and 70% with averages of 62 to 64%). But stand structure and species composition were changed dramatically and the amount of growing-stock capital left in residual stands varied widely, as did growth responses. For example, residual basal area ranged from 66 to 96 ft^2/ac (15 to 22 m^2/ha), and residual board volume ranged from 409 to 3,800 mbf/ac (5 to 44 m^3/ha). Furthermore, the several treatments varied widely in the amount of crown release afforded the residuals. The thin from below provided very little opening in the main crown canopy, whereas the thin from above removed it almost completely. Species composition and average tree size were altered dramatically, and in different directions, by the several treatments. So, it is not surprising that important growth differences were observed as a result of changes in stand structure, even though relative density was constant. It seems clear that both density and structure (and therefore, species composition) need to be controlled during thinning in stands such as these, to ensure that desired growth responses are obtained.

In young, stratified hardwood stands where saplings represent a large proportion of the total basal area, we recommend that thinning either include noncommercial removal of some of the saplings, or that thinning be delayed until the stand is a little older and the sapling component has declined in importance. Trees removed during thinning should include poor-quality individuals of all sizes and species, but cutting of acceptable quality trees should be concentrated in the smaller-size classes and lower-value species. While thinning must include opening of the main crown canopy to ensure a growth response, the residual stand should be dominated by the largest trees of the high-value species. More specific recommendations on residual stand structure are given in Marquis et al. 1984.

One of the supplementary findings from this study is that the stocking measure used to control thinning did not work well when stand structure was dramatically altered. This stocking parameter is intended to provide a measure of the relative density (or relative degree of crowding) in stands that vary in tree size or species composition. Several studies have shown its superiority over absolute measures of density (such as basal area or volume) for this purpose (Stout et al. 1987). Although this problem meant that the original objective of equal densities for all thinning treatments was not precisely met, there is currently no better measure available. Attempts to develop a measure that overcomes this problem are currently underway.

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