Stand dynamics in 60-year-old Allegheny hardwoods after thinning

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Abstract: Stand dynamics and tree growth in even-aged hardwood stands can be influenced by manipulating relative stand density, species composition, and stand structure. Land managers need quantitative information on the effect of vegetation manipulation to prescribe stand treatments that are appropriate for specific management objectives. Sixty-year-old stands composed of black cherry (*Prunus serotina* Ehrh.), red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* Marsh.), and American beech (*Fagus grandifolia* Ehrh.) were thinned to 45, 60, and 75% relative density as measured by the stocking guide for Allegheny hardwoods. Stand age, aspect, elevation, and soil–site conditions were uniform among the study plots, while relative density and to a lesser degree stand structure were altered by the thinning treatments. Regression analyses were used to relate stand dynamics and tree diameter growth over a 10-year period to changes in relative density, stand structure, and species composition. Stand growth is reported in basal area, cubic volume, sawtimber volume, and relative density growth, and individual tree response is reported in terms of diameter growth by species group. Study results generally support current recommendations for thinning Allegheny hardwoods for wood volume production, though stands with relatively high proportions of black cherry may respond better to densities greater than recommended levels for optimal sawtimber volume production. These results also may be useful for interpreting overall stand dynamics and developing prescriptions to enhance production of other woodland benefits.

Résumé : La dynamique du peuplement et la croissance des arbres dans les peuplements feuillus équiennes peuvent être modifiées en manipulant la densité relative du peuplement, la composition en espèces et la structure du peuplement. Les aménagistes forestiers ont besoin d'informations quantitatives sur l'effet de la manipulation de la végétation afin de prescrire les traitements appropriés en fonction des objectifs spécifiques d'aménagement. Des peuplements de 60 ans composés de cerisier tardif (*Prunus serotina* Ehrh), d'érable rouge (*Acer rubrum* L.), d'érable à sucre (*Acer saccharum* Marsh.) et de hêtre à grandes feuilles (*Fagus grandifolia* Ehrh.) ont été éclaircis de manière à obtenir des densités relatives de 45, 60 et 75%, telles que mesurées à l'aide du guide de densité relative des feuillus des massifs alleghaniens. L'âge, l'exposition et l'altitude des peuplements, ainsi que les caractéristiques du sol et du site, étaient uniformes pour l'ensemble des parcelles étudiées tandis que la densité relative et, dans une moindre mesure, la structure du peuplement ont été modifiées par les traitements d'éclaircie. Les relations entre la dynamique du peuplement ou la croissance en diamètre des arbres sur une période de 10 ans et les changements dans la densité relative, la structure du peuplement et la composition en espèces ont été testées par l'analyse de régression. La croissance du peuplement est exprimée en surface terrière, volume de matière ligneuse, volume de bois d'oeuvre et augmentation de la densité relative; la réaction individuelle des arbres est exprimée en croissance en diamètre par groupe d'espèces. En général, les résultats de l'étude supportent les recommandations en usage concernant l'éclaircie des feuillus dans les massifs alleghaniens pour la production de matière ligneuse. Par contre, les peuplements qui ont une proportion relativement élevée de cerisier tardif pourraient réagir mieux à des densités plus fortes que celles qui sont recommandées pour la production optimale de bois d'oeuvre. Ces résultats peuvent également être utiles pour interpréter la dynamique d'ensemble des peuplements et pour développer des prescriptions visant à améliorer la production d'autres ressources en provenance des terres boisées.
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Introduction

As an even-aged hardwood stand matures, competition for light, water, or soil nutrients inhibits the growth of individual trees and causes some trees to die. Natural tree mortality results in a temporary reduction in stand density, and the additional growing space and site resources become available to the residual trees. Many of the residual trees grow faster, stand density increases once again, and the stand structure advances to a more mature stage of development characterized by a larger average tree diameter and fewer trees per hectare. Land managers can prescribe cutting treatments to regulate tree growth and to some degree control stand development by thinning to an appropriate residual stand density and structure. Of course, the appropriate thinning treatment would be directly related to production objectives. For example, increased basal area or cubic volume growth are important management objectives for fiber or pulpwood production, respectively. Maximum growth for these two products may occur at different thinning levels, so the manager needs information on many aspects of stand dynamics in order to prescribe the appropriate treatment.

For sawtimber production, properly planned thinnings meet three major objectives: (1) concentrate growth on the most desirable trees, (2) reduce the time required to yield products of a desired size and quality, and (3) increase product yield by harvesting and utilizing trees that would die in the absence of thinning. Equations for measuring relative stand density (RD) and practical guidelines for manipulating RD and stand structure

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in Allegheny hardwoods were presented by Roach (1977) and later modified by Marquis (1986, 1994). These guidelines were based on studies in northwestern Pennsylvania where the predominant management objective is the production of high-quality black cherry (*Prunus serotina* Ehrh.) sawtimber and veneer. An important question is whether current guidelines are suitable for similar stands in other parts of the Appalachian hardwood region and for other product objectives.

A thinning study was installed in 60-year-old Allegheny hardwood stands in central West Virginia to test the applicability of Roach's (1977) guidelines in the central Appalachians. A primary objective of this study was to quantify the effect of manipulating RD on stand dynamics for use in developing guidelines for producing wood products and other benefits. Previous reports from this study analysed logging economics (Miller and Sarles 1986), logging damage to the residual stand (Lamson et al. 1984), and 5-year growth results (Lamson and Smith 1988). This report relates stand dynamics and tree diameter growth over a 10-year period to changes in relative density, stand structure, and species composition. Stand growth is reported in basal area, cubic volume, sawtimber volume, and relative density growth. Individual-tree response is reported in diameter growth by species group. This information can be used to evaluate current thinning recommendations and determine the appropriate RD and stand structure necessary to meet objectives involving wood product yields or other outputs related to stand density and structure in similar stands.

This report also includes a comparison of methods for analysing plot data in thinning trials. The comparison illustrates how cluster analysis of pretreatment conditions and regression analysis using continuous treatment levels clarify the effect of RD on stand growth compared with a more traditional approach in which discrete treatment levels are used.

Study area

The study plots are located on the Monongahela National Forest within the Loop Road Research Area in northern Pocahontas County, West Virginia (38°41′N, 79°43′W). Elevation ranges from 1080 to 1104 m on a southwest aspect. The landforms include mostly convex ridgetops and sideslopes where slope ranges from 5 to 20%. The soil series is consistent throughout the study area, recently described as Mandy channery silt loam (loamy-skeletal, mixed, frigid Typic Dystrochrept) (USDA Soil Conservation Service 1994). Soil depth within the study plots ranges from 55 to 70 cm. Annual precipitation averages 147 cm distributed throughout the year, and the growing season averages 144 frost-free days.

Treatments were applied in unmanaged, 60-year-old, even-aged stands. These stands originated following heavy timber cutting in virgin forests around 1920. When the study began, the overstory was predominantly black cherry with some white ash (*Fraxinus americana* L.) and red maple (*Acer rubrum* L.). Most red maple was in the intermediate crown class, occupying the midstory stratum. The understory included American beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), and striped maple (*Acer pensylvanicum* L.). Site index for black cherry in the study area is 23 m at base age 50 years. Ecological land type for the study area was defined by the Monongahela National Forest and is located within M221B, the Allegheny Mountain Section of the Central Appalachian Broadleaf Forest Province (McNab and Avers 1994).

Methods

Published guidelines for managing Allegheny hardwoods recommend thinning immature cherry–maple stands to approximately 60% RD (Roach 1977). At this density, stand growth is concentrated efficiently on a reduced number of desirable trees, while full utilization of the site is maintained. This target residual stocking level was based on data from undisturbed even-aged stands and early results from a thinning study on the Allegheny plateau in northwestern Pennsylvania. To test the applicability of these guidelines in the central Appalachians, this study included four treatments: 45, 60, 75% RD, and control. RD was measured according to stocking equations published by Roach (1977). The treatment levels were chosen to obtain response data from a range of residual densities, including the recommended treatment, so that a target residual density appropriate for stands in the central Appalachians could be derived.

In the fall of 1981, 23 square growth plots, each 0.2 ha, were installed and all trees 2.5 cm diameter breast height (DBH) and larger were inventoried to determine initial stocking levels. Each growth plot was surrounded by a similarly treated buffer strip that was 23 m wide; thus a plot and its buffer totalled approximately 0.8 ha. Five plots were randomly assigned as controls, while six plots each were randomly assigned to the three thinning treatments, for a total of 18 thinned plots. Cut trees in the growth plots and buffer strips within each treatment area were marked to achieve a certain residual stand density. As plots were marked for thinning, an attempt was made to remove two-thirds of the cut basal area from below the average diameter for the black cherry and red maple species groups as recommended by Roach (1977).

All residual trees 2.5 cm DBH and larger within the 0.2-ha growth plots were permanently tagged for long-term monitoring (Lamson and Rosier 1984). Species, DBH, crown class, and coded remarks were recorded for each tree before and immediately after logging. The plots were remeasured 2, 5, 7, and 10 years after logging. The plots were thinned in the dormant season of 1981–1982 by a three-person logging crew using chain saws and a wheeled skidder. Merchantable trees 17.8 cm DBH and larger were topped at 10.2 cm diameter inside bark (DIB) and skidded full length. Cut trees less than 17.8 cm DBH were not skidded. Each growth plot with its buffer was logged as a separate unit.

Data analysis

Five-year results from this study indicated little differences in growth response among treatments (Lamson and Smith 1988), raising concern that subtle variation among plots was masking the effect of RD on growth. To account for such variation, initial stand structure and species composition were analysed by cluster analysis to identify groups of plots with similar pretreatment characteristics. This method of grouping similar plots prior to evaluating growth response was useful in accounting for plot variation in a previous thinning study (Nowak 1996). Ten variables were used in the analysis: total number of stems per hectare, total basal area per hectare, and relative number of stems and relative basal area for black cherry, red maple, sugar maple, and American beech. Plots were assigned to groups using a hierarchical clustering procedure based on Ward's linkage method (SYSTAT 1992). After plots were assigned to groups, the 10 variables used in the cluster analysis were compared by analysis of variance (ANOVA), and mean basal area distributions by species were graphed to clarify the differences among plot clusters.

Analysis of stand growth

The RD per hectare was computed for each plot before and after treatment using updated equations for the Allegheny hardwoods stocking guide (Stout et al. 1987). This caused the levels of RD applied to each plot to become more like a continuous range of treatments for the purpose of the regression analyses. All trees 2.5 cm DBH and larger were included in the computation of RD. Basal area growth and volume growth also were computed for each plot. Threshold DBH for growth computations were 2.5 cm for basal area, 12.7 cm for cubic volume, and 27.9 cm for sawtimber volume. Cubic volume to a 10.2-cm DIB top and sawtimber volume to a 20.3-cm DIB top were computed using local volume equations (International 0.25-in. rule) developed for the Fernow Experimental Forest. Growth was assigned to the following growth components (Beers 1962; Marquis and Beers 1969):

Survivor growth: includes trees whose initial DBH was equal to or greater than the threshold DBH before treatment and were present at the beginning and end of the measurement period.

Ingrowth: includes trees whose initial DBH became equal to or greater than the threshold DBH after treatment and were present at the end of the measurement period.

Gross growth: includes survivor growth plus ingrowth.

Mortality: includes trees whose initial DBH was equal to or greater than the threshold DBH before treatment and died during the measurement period.

Net growth: includes survivor growth plus ingrowth minus mortality.

Regression equations were developed to predict survivor growth, ingrowth, gross growth, mortality, and net growth as functions of RD. Equations were fit using separate data sets for basal area, cubic volume, and sawtimber volume growth. Least-squares regression was used with RD and RD^2 as independent variables. The dependent variable in each equation was annual growth per hectare. Intercept and slope coefficients were compared between clusters of plots using dummy variables (Cunia 1973; Nowak 1996).

Additional regression analyses were conducted to model the annual increase in RD as a linear function of post-treatment RD, periodic sawtimber volume production (cut volume plus ending volume) as a quadratic function of RD, and net sawtimber volume growth as a quadratic function of the percentage of RD cut from below the average stand diameter. The average stand diameter used to compute RD cut from below is the medial diameter, the midpoint of the stand basal area distribution, and is the average of the diameter class midpoints weighted by the proportion of basal area in that class (Marquis et al. 1992).

Analysis of DBH growth by species

Initially, ANOVA was used to relate 10-year DBH growth of individual trees to the intended residual RD on each plot, a discrete variable. Initial DBH was included as a covariate factor for determining adjusted means. Pairwise comparisons of mean DBH growth for each treatment were made using the Tukey–Kramer honestly significant difference test. The four major species, black cherry, red maple, sugar maple, and American beech, were analyzed separately.

A sequence of least-squares linear regression equations were fit using survivor-tree data to determine the relationship between 10-year DBH growth and actual residual RD, a continuous variable. The following three-step regression analysis was conducted separately for each species. Step 1: a regression equation was fit for each plot to predict 10-year DBH growth as a function of initial DBH. Step 2: a regression equation was fit to predict the estimated slope coefficient from the initial regression as function of RD on each plot. Step 3: a regression equation was fit to predict mean 10-year DBH growth per tree as a function of RD. Steps 1 and 2 were used to account for initial DBH as a covariate factor affecting DBH growth and to detect differences in regression slopes by RD, that is, the interaction between initial DBH and RD in predicting DBH growth. Step 3 was used to detect differences in regression intercepts, that is, the significance of RD as a factor affecting DBH growth.

Separate multiple linear regression equations were fit for black cherry, red maple, sugar maple, and American beech using survivor-tree data from all plots to predict 10-year DBH growth as a function of two independent variables: initial DBH and RD. Equations estimated from data pooled for all plots were compared with equations estimated from plot data grouped by cluster analysis using a dummy variable approach (Cunia 1973). The estimated slope and intercept coefficients were compared using *F*-tests to detect significant reductions in regression sums of squares resulting from grouping plots according to pretreatment species composition. Results obtained from data pooled for all plots were graphed for each species to illustrate the effect of RD on DBH growth over the range of initial DBH in the data set.

Results

For all plots, RD averaged 110% before thinning treatments were applied (Table 1). The plots were overstocked, and mortality among trees in weaker crown positions was evident. For each thinning treatment, trees were removed from a range of size classes to properly distribute the cut. For example, thinning to 60% RD entailed cutting an average of 395 poletimber and 47 sawtimber trees/ha. For this treatment, the residual stand averaged 245 poletimber and 114 sawtimber trees/ha, while residual basal area averaged 8.70 and 9.78 m^2/ha for poletimber and sawtimber, respectively. A postlogging inventory indicated that logging damage to the residual stand was concentrated in the sapling stems and resulted in RD slightly lower than intended for each treatment. Average harvest volumes ranged from 11.3 to 46.2 m^3/ha.

Analysis of growth based on discrete levels of RD

There was not a significant difference in average net basal area growth among the three thinning treatments, though all thinning treatments increased net basal area growth compared with controls (Table 2). Net growth averaged 7.44 m^2/ha on the thinned plots and 3.70 m^2/ha on the control plots. Most of the increase in net basal area growth resulted from a substantial reduction in mortality on the thinned plots. Mortality averaged 3.56 m^2/ha on the control plots and 0.63 m^2/ha on the thinned plots. In general, ingrowth increased and mortality decreased as RD decreased, though ingrowth accounted for a small proportion of net growth for control plots and plots thinned to 75 and 60% RD. Ingrowth averaged 0.78 m^2/ha on the plots thinned to 45% RD and 0.14 m^2/ha on all other plots. Survivor growth was least for plots thinned to 45% RD because these plots had relatively few residual trees compared with the other treatments.

Results indicated that light thinnings are advisable for increasing net cubic volume growth. Plots thinned to 75% and 60% RD had greater net cubic volume growth than controls or plots thinned to 45% RD (Table 2). Thinning to 45% RD left fewer residual trees and greatly reduced survivor growth compared to other treatments. Survivor growth averaged 46.8 m^3/ha on plots thinned to 45% RD and 57.6 m^3/ha on all other plots. For control plots, net cubic volume growth was reduced relative to thinned plots because of greater mortality resulting from overcrowding. Mortality averaged 9.8 m^3/ha for control plots and only 1.23 m^3/ha for thinned plots. Ingrowth increased as RD decreased on the thinned plots, though ingrowth accounted for a relatively small proportion of net cubic volume for plots thinned to 75 and 60% RD.

There was not a significant increase in net sawtimber volume growth due to thinning after 10 years, though the average net sawtimber volume growth was slightly greater on plots

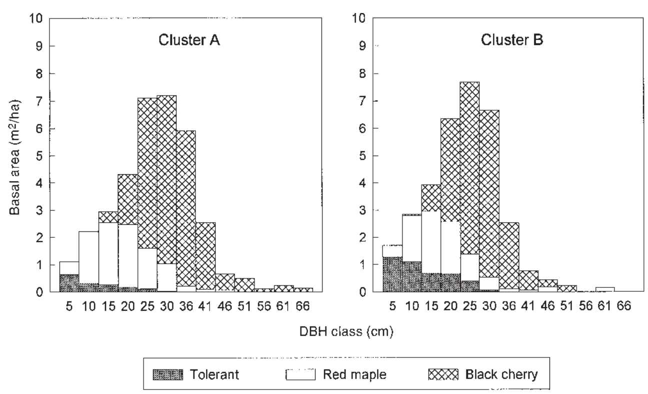
Table 1. Per hectare stand data by thinning treatment.

	No. of trees/ha			Basal area (m^2/ha)			Vol. (m^3/ha)†		RD (%)
Inventory	≥2.5cm*	≥12.7cm*	≥27.9cm*	≥2.5cm	≥12.7cm	≥27.9cm	≥12.7cm	≥27.9cm	≥2.5cm
45% (*n*=5)									
Initial	1868	754	195	38.14	33.89	16.51	218.1	124.1	119
Cut	1053	489	79	22.39	19.40	6.50	120.0	46.2	77
Residual	815	265	116	15.75	14.49	10.01	98.1	77.9	42
10-year	1507	334	158	23.10	21.10	16.55	147.1	150.9	60
60% (*n*=6)									
Initial	2093	801	161	38.64	33.71	13.48	215.0	100.0	110
Cut	946	442	47	17.70	15.23	3.70	92.2	24.5	54
Residual	1147	359	114	20.94	18.48	9.78	122.8	75.5	56
10-year	1201	395	195	28.40	25.53	18.76	179.6	155.9	71
75% (*n*=6)									
Initial	2021	768	168	38.16	33.87	15.04	218.8	116.9	104
Cut	699	299	22	11.16	9.07	1.70	52.9	11.3	35
Residual	1322	469	146	27.00	24.80	13.34	165.9	105.6	69
10-year	1349	482	222	34.51	31.75	22.00	224.4	187.1	83
Control (*n*=4)									
Initial	2132	712	173	37.72	32.95	16.42	210.9	137.7	106
10-year	1715	692	237	41.42	38.27	24.15	258.4	212.3	105

*DBH.

†Sawtimber volume, 1 m^3/ha = 71.4 bd ft/acre, International 0.25-in. rule.

Fig. 1. Basal area distribution before treatment by species group for clusters A and B.



thinned to 75 and 60% RD (Table 2). Net sawtimber volume growth averaged 81.0 m^3/ha on plots thinned to 75 and 60% RD, and 73.8 m^3/ha on plots thinned to 45% RD and controls. Thinning concentrated growth on fewer trees, as indicated by similar survivor growth for thinned and control plots. In addition, ingrowth was slightly greater for plots thinned to 60 and 75% RD than for plots thinned to 45% RD and controls. Ingrowth accounted for 38, 34, and 26% of net sawtimber volume growth on plots thinned to 60, 75, and 45% RD, respectively. Mortality was similar among the treatments, averaging 2 sawtimber trees/ha.

Analysis of growth based on continuous variation in RD

The analysis of average growth response based on discrete levels of RD did not reveal specific treatments that maximized net basal area, cubic volume, or sawtimber volume growth (Table 2). However, a further examination of growth based on continuous variation of RD using cluster and regression analyses provided a means for identifying specific minimum and maximum points for each growth component.

The cluster analysis of pretreatment stand structure and species composition revealed two groups of plots, 12 plots in cluster A and 9 plots in cluster B (Table 3). Each cluster included two control plots and at least one plot from each of the thinning treatments; thus, a complete range of residual RD was represented in each cluster. One control plot and one plot thinned to 45% RD were allocated to a third cluster based on relatively high proportions of white ash. This cluster did not represent the range of all treatments and was dropped from the analysis.

While plots in clusters A and B had equal average total basal area (38.3 m^2/ha), the clusters differed with respect to relative number of stems or relative basal area in each species (Table 3). Plots in cluster A had less sugar maple and American beech basal area, and more black cherry and red maple basal area, than plots in cluster B. Plots in cluster A also had fewer total stems and a larger average stand diameter. Bar graphs of pretreatment basal area distributions indicated that a lower proportion of shade-tolerant species in the understory for cluster A was associated with more and larger black cherry in the overstory (Fig. 1). Black cherry had reached 66 cm DBH in cluster A but only 51 cm DBH in cluster B.

Differences in pretreatment plot characteristics remained somewhat intact after thinning. For example, after thinning to 60% RD, plots in cluster A continued to have more black cherry, a larger average stand diameter, and less basal area in tolerant understory species than plots in cluster B (Fig. 2). While thinning reduced RD by as much as 70% on some plots, trees were cut from a range of size classes, and species composition was altered to a much lesser degree.

A general result of the regression analyses was that the estimated slope coefficients were equal and the estimated intercept

Table 2. Ten-year summary of stand growth and mortality by thinnng treatment.

Treatment	Residual	10-year	Survivor growth*	Ingrowth	Mortality	Net growth	HSD†
			Basal area (m^2/ha)				
45%	15.75	23.10	7.09 (756)	0.78 (751)	0.52 (111)	7.35	*a*
60%	20.94	28.40	7.90 (986)	0.21 (215)	0.65 (161)	7.46	*a*
75%	27.00	34.51	8.06 (1174)	0.16 (175)	0.71 (148)	7.51	*a*
Control	37.72	41.42	7.21 (1708)	0.05 (74)	3.56 (558)	3.70	*b*
			Cubic volume (m^3/ha)				
45%	98.1	147.1	46.8 (255)	3.0 (79)	0.8 (7)	49.0	*a*
60%	122.8	179.6	56.0 (351)	1.5 (44)	0.7 (7)	56.8	*b*
75%	165.9	224.4	60.3 (460)	0.4 (20)	2.2 (10)	58.5	*b*
Control	210.9	258.4	56.6 (630)	0.7 (59)	9.8 (79)	47.5	*a*
			Sawtimber volume (m^3/ha)‡				
45%	77.9	150.9	54.7 (114)	18.7 (44)	0.4 (2)	73.0	*a*
60%	75.5	155.9	49.7 (114)	30.7 (82)	0	80.4	*a*
75%	105.6	187.1	54.5 (146)	27.6 (77)	0.6 (2)	81.5	*a*
Control	137.7	212.3	53.6 (171)	21.7 (67)	0.8 (2)	74.5	*a*

*Number of stems per hectare is given in parentheses.

†For each unit of measure, rows followed by the same letters are not significantly different, $P > 0.01$, based on Tukey–Kramer honestly significant difference test (HSD).

‡Sawtimber volume, 1 m^3/ha = 71.4 bd ft/acre, International 0.25-in. rule.

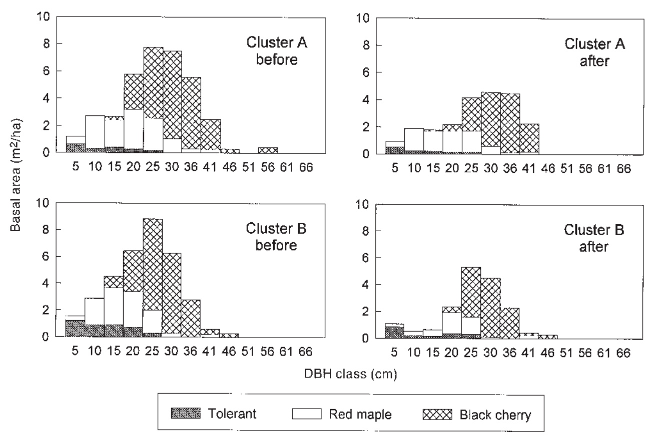
Table 3. Comparison of average pretreatment stand species composition between clusters of study plots.

Variable	Cluster A (n=12) Mean	Cluster A (n=12) SE	Cluster B (n=9) Mean	Cluster B (n=9) SE	*P*-value
Total no. stems/ha	1796	60.3	2335	69.4	<0.01
Total basal area (m^2/ha)	38.3	0.6	38.3	0.7	0.91
Relative number (% of total)					
Black cherry	20.3	1.6	17.8	1.8	0.32
Red maple	37.0	2.6	26.0	3.0	0.01
American beech	22.6	2.8	25.9	3.3	0.47
Sugar maple	7.2	4.6	19.0	5.3	0.11
Relative basal area (% of total)					
Black cherry	61.5	1.9	54.4	2.2	0.02
Red maple	25.6	2.4	21.6	2.8	0.29
American beech	1.6	0.4	3.1	0.4	0.02
Sugar maple	2.5	1.7	8.1	2.0	0.05

coefficients were different between plot clusters A and B for each growth component (Table 4). For example, the estimated slope coefficients were equal ($p = 0.7531$) and the estimated intercept coefficients were different ($p < 0.01$) for equations relating net basal area growth to RD for plot clusters A and B. This result was observed for each component of growth (net, ingrowth, survivor, mortality, and gross) and for each unit of measure (basal area, cubic volume, and sawtimber volume).

For basal area growth, the estimated equations with equal slopes and unique intercepts for each cluster had R^2 values that ranged from 0.89 to 0.99 (Table 5*b*). Net growth was greater for plots in cluster B, those plots with greater proportions of sugar maple and American beech in the understory before treatment. Net basal area growth peaked at 52% RD (Fig. 3).

Fig. 2. Basal area distribution before and after thinning to 60% RD for clusters A and B.



For cubic volume growth, the estimated equations with equal slopes and unique intercepts for each cluster had R^2 values that ranged from 0.52 to 0.99 (Table 6*b*). Net cubic volume growth was greater for plots in cluster B. Mortality increased as RD increased, resulting in declining net growth at RD greater than 70%. Ingrowth decreased as RD increased, athough ingrowth was less than 1 $m^3 \cdot ha^{-1} \cdot year^{-1}$ and had little impact on net growth. Net cubic volume growth peaked at 70% RD (Fig. 4).

For sawtimber volume growth, the estimated equations with equal slopes and unique intercepts for each cluster had R^2 values that ranged from 0.26 to 0.99 (Table 7*b*). Net sawtimber volume growth was greater for plots in cluster B, consistent

Table 4. Comparison of estimated regression slope and intercept coefficients between clusters of plots for each growth component and unit of measure.

	df	*P*-values for comparisons				
		Net	Ingrowth	Survivor	Mortality	Gross
Basal area						
Slope	2/15	0.7531	0.2995	0.5667	0.9609	0.6850
Intercept	1/17	<0.01	<0.01	<0.01	<0.01	<0.01
Cubic volume						
Slope	2/15	0.5522	0.1645	0.1614	0.1085	0.4498
Intercept	1/17	<0.01	<0.07	<0.01	<0.01	<0.01
Sawtimber volume						
Slope	2/15	0.8004	0.6935	0.7707	0.2539	0.9871
Intercept	1/17	<0.01	<0.01	<0.01	<0.057	<0.01

Fig. 3. Basal area growth as a function of RD for regression equations with equal slope and unique intercept.

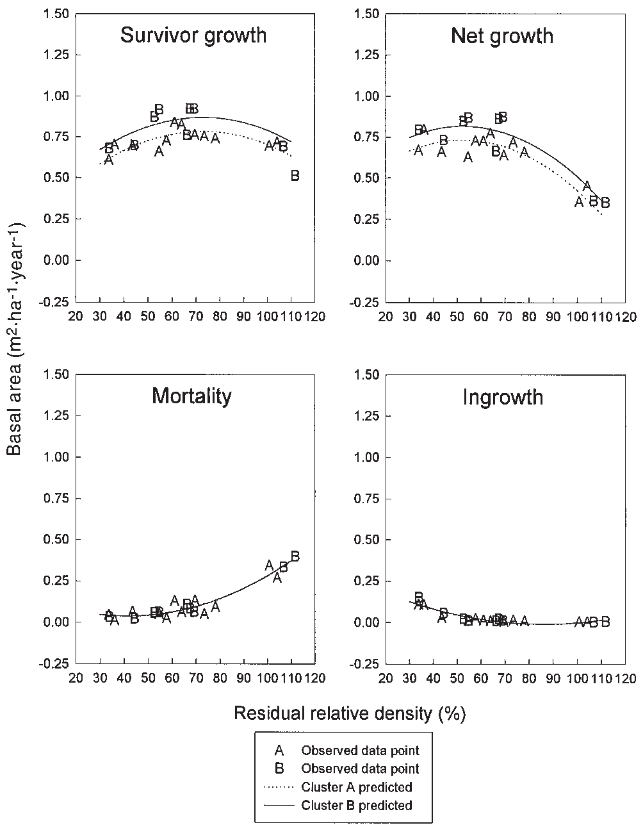
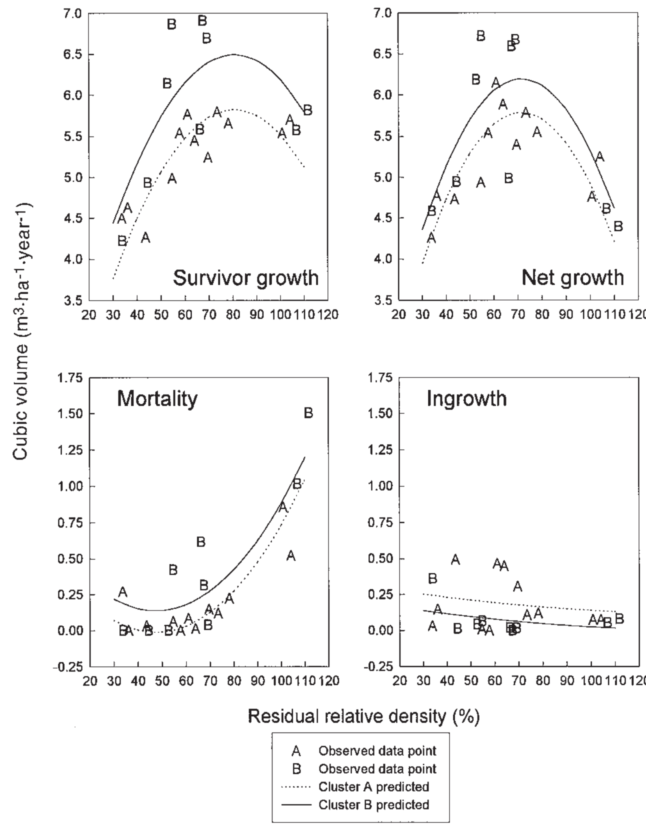


Fig. 4. Cubic volume growth as a function of RD regression equations with equal slope and unique intercept.



with basal area and cubic volume growth. In general, net growth increased as RD decreased and peaked at 43% RD, although the estimated regression slope coefficents were not significantly different from zero for this growth component. Thus, solely on the basis of increment, the results indicate that net sawtimber volume growth was maximized over a relatively wide range of RD (Fig. 5).

Further analyses based on periodic sawtimber volume production, which includes volume harvested in thinnings plus volume present at the end of the measurement period, revealed more specific guidelines. A quadratic model with no intercept relating sawtimber production to RD for thinned plots ($n = 17$, $P < 0.01$, $R^2 = 0.93$) indicated that maximum sawtimber production occurred at 62% RD for cluster A and 48% RD for cluster B (Fig. 6). Thus, as the proportion of black cherry in the plots increased, the RD at which sawtimber volume production peaked also increased.

Stand structure also affected sawtimber volume growth. On the basis of post-treatment inventories of all thinned plots, the percentage of RD cut from below the medial stand diameter varied from 52 to 93%. A quadratic model relating net sawtimber volume growth to the percentage of RD cut from below ($n = 17$, $P < 0.01$, $R^2 = 0.99$) indicated that maximum net sawtimber volume growth occurred where 78% of the cut included trees less than the medial stand diameter, the same for plots in cluster A and B (Fig. 7).

Table 5. Regression parameters from basal area growth equations.

(*a*) Regression parameters from basal area growth equations fit to data combined for all plots.

		Regression coefficient				
Dependent variable	*n*	b_0	b_1	b_2	$S_{y,x}$	R^2
Net growth	21	1.86	0.0574	–0.000 557	0.364	0.77
Ingrowth	21	1.36	–0.0325	0.000 189	0.077	0.83
Survivor growth	21	1.22	0.0636	–0.000 433	0.326	0.39
Mortality	21	0.70	–0.0258	0.000 311	0.148	0.92
Gross growth	21	2.56	0.0315	–0.000 246	0.333	0.22

Note: Model: $y = b_0 + b_1$ RD + b_2 RD$^2 + e$, where *y* is basal area (ft^2·acre^{-1}·year^{-1}), *b* estimated regression coefficients, RD is relative density, and *e* is error (1 ft^2/acre = 0.2296 m^2/ha).

(*b*) Regression parameters from basal area growth equations with equal slope and unique intercept for each cluster.

		Regression coefficient					
Dependent variable	*n*	b_{10}	b_{20}	b_1	b_2	$S_{y,x}$	R^2
Net growth	21	1.56	1.93	0.0623	–0.000 594	0.314	0.99
Ingrowth	21	1.35	1.36	–0.0325	0.000 189	0.079	0.89
Survivor growth	21	0.91	1.29	0.0686	–0.000 470	0.265	0.99
Mortality	21	0.69	0.70	–0.0257	0.000 310	0.153	0.96
Gross growth	21	2.25	2.63	0.0366	–0.000 284	0.271	0.99

Note: Model: $y = b_{i0} + b_1$ RD + b_2 RD$^2 + e$, where y = basal area (ft^2·acre^{-1}·year^{-1}), *b* is estimated regression coefficients, *i* is cluster, RD is relative density, and *e* = error (1 ft^2/acre = 0.2296 m^2/ha).

(*c*) Regression parameters from basal area growth equations with unique slope and intercept for each cluster.

		Regression coefficient							
Dependent variable	*n*	b_{10}	b_{20}	b_{11}	b_{21}	b_{12}	b_{22}	$S_{y,x}$	R^2
Net growth	21	1.92	1.63	0.0494	0.0726	–0.000 492	–0.000 670	0.328	0.99
Ingrowth	21	1.25	1.60	–0.0303	–0.0388	0.000 180	0.000 224	0.078	0.91
Survivor growth	21	1.42	0.62	0.0526	0.0882	–0.000 356	–0.000 597	0.272	0.99
Mortality	21	0.73	0.60	–0.0264	–0.0232	0.000 312	0.000 296	0.162	0.96
Gross growth	21	2.64	2.23	0.0230	0.0494	–0.000 180	–0.000 373	0.281	0.99

Note: Model: $y = b_{i0} + b_{i1}$ RD + b_{i2} RD$^2 + e$, where *y* is basal area (ft^2·acre^{-1}·year^{-1}), *b* is estimated regression coefficients, *i* is cluster, RD is relative density, and *e* is error (1 ft^2/acre = 0.2296 m^2/ha).

Forest managers often need to estimate the rate of increase in RD after thinning treatments to estimate long-term growth and to plan subsequent silvicultural activities. A linear regression equation fit using data from all plots ($n = 21$, $P < 0.01$, $R^2 = 0.87$) indicated a strong relationship between residual RD and annual increase in RD after thinning (Fig. 8). For control plots RD did not change over the study period. For thinned plots, the annual increase in RD ranged from 1.4 to 1.8% within the range of the treatments, increasing as residual RD decreased.

DBH growth by species

The four species examined in this study differed with respect to relative initial DBH and crown position. For black cherry, the initial DBH averaged 29.5 cm, and 94% of survivor stems were codominant or dominant (Table 8). By contrast, red maple averaged 13.0 cm DBH and only 16% of survivor stems were codominant. Sugar maple and American beech were predominantly understory components, with initial DBH averaging 7.3 and 4.3 cm, respectively. Only 5% of sugar maple and none of the American beech survivors were codominant. The minimum DBH of codominant trees was about 17.8 cm for black cherry and sugar maple and 14.5 cm for red maple.

For each species, average DBH growth significantly increased with each incremental reduction in RD (Table 8). For black cherry, predominant in the overstory, thinning to 45% RD increased DBH growth by 76% compared with trees in control plots. For red maple, pimarily a midstory component in the study plots, heavy thinning increased DBH growth by 167%. Growth of sugar maple and American beech in the understory increased by more than 500% in heavily thinned stands.

The estimated simple linear regression equations relating DBH growth to initial DBH were significant for all plots and species ($P < 0.01$). Regressions relating average DBH growth on each plot to RD also were significant for each species ($n = 21$, $P < 0.01$). These results indicated that DBH growth is a function of RD and that initial DBH is a covariate factor affecting growth. Slope coefficients from the initial regressions relating growth to initial DBH on each plot were not significantly related to RD ($n = 21$, $P > 0.5$), indicating that there is no significant interaction between initial DBH and RD in predicting DBH growth.

In the multiple linear regression analysis, DBH growth of individual trees was related to initial DBH and RD for each species. Regression coefficients for each variable were significant ($P < 0.01$) when equations were fit using data from all plots combined, and for data grouped into two clusters representing

Table 6. Regression parameters from cubic volume growth equations.

(*a*) Regression parameters from cubic volume growth equations fit to data combined for all plots.

Dependent variable	n	Regression coefficient			$S_{y,x}$	R^2
		b_0	b_1	b_2		
Net growth	21	9.48	2.1030	–0.014 658	7.54	0.58
Ingrowth	21	3.37	–0.0192	–0.000 027	2.43	0.05
Survivor growth	21	16.35	1.7273	–0.010 551	8.19	0.49
Mortality	21	10.24	–0.3948	0.004 080	2.73	0.80
Gross growth	21	19.72	1.7081	–0.010 578	7.43	0.52

Note: Model: $y = b_0 + b_1\ \mathrm{RD} + b_2\ \mathrm{RD}^2 + e$, where y is cubic volume ($\mathrm{ft}^3\cdot\mathrm{acre}^{-1}\cdot\mathrm{year}^{-1}$), b is estimated regression coefficients, RD is relative density, and e is error (1 ft^3/acre = 0.07 m^3/ha).

(*b*) Regression parameters from cubic volume growth equations with equal slope and unique intercept for each cluster.

Dependent variable	n	Regression coefficient				$S_{y,x}$	R^2
		b_{10}	b_{20}	b_1	b_2		
Net growth	21	4.77	10.58	2.1791	–0.015 231	7.08	0.99
Ingrowth	21	4.69	3.06	–0.0405	0.000 134	2.34	0.52
Survivor growth	21	8.58	18.16	1.8528	–0.011 497	6.61	0.99
Mortality	21	8.51	10.65	–0.3667	0.003 868	2.55	0.89
Gross growth	21	13.28	21.23	1.8123	–0.011 363	6.29	0.99

Note: Model: $y = b_{i0} + b_1\ \mathrm{RD} + b_2\ \mathrm{RD}^2 + e$, where y is cubic volume ($\mathrm{ft}^3\cdot\mathrm{acre}^{-1}\cdot\mathrm{year}^{-1}$), b is estimated regression coefficients, i is cluster, RD is relative density, and e is error (1 ft^3/acre = 0.07 m^3/ha).

(*c*) Regression parameters from cubic volume growth equations with unique slope and intercept for each cluster.

Dependent variable	n	Regression coefficient						$S_{y,x}$	R^2
		b_{10}	b_{20}	b_{11}	b_{21}	b_{12}	b_{22}		
Net growth	21	16.28	1.01	1.7666	2.5054	–0.011 966	–0.017 638	7.25	0.99
Ingrowth	21	–3.07	12.58	0.2086	–03256	–0.001 665	0.002 013	2.21	0.62
Survivor growth	21	30.61	–9.76	1.1543	2.6813	–0.006 508	–0.016 906	6.22	0.99
Mortality	21	11.25	1.81	–0.4037	–0.1497	0.003 792	0.002 745	2.34	0.92
Gross growth	21	27.54	2.82	1.3629	2.3557	–0.008 173	–0.014 893	6.35	0.99

Note: Model: y is $b_{i0} + b_{i1}\ \mathrm{RD} + b_{i2}\ \mathrm{RD}^2 + e$, where y is cubic volume ($\mathrm{ft}^3\cdot\mathrm{acre}^{-1}\cdot\mathrm{year}^{-1}$), b is estimated regression coefficients, i is cluster, RD is relative density, and e is error (1 ft^3/acre = 0.07 m^3/ha).

pretreatment species composition. Fit was not improved using quadratic or interaction terms. Regression slopes were equal within each species ($P > 0.49$), while intercepts were different ($P < 0.05$) (Tables 9*a* and 9*b*). R^2 values ranged from 0.37 to 0.63 for data from all plots. Grouping data by pretreatment species composition resulted in less unexplained variation, and R^2 values ranged from 0.76 to 0.91 for equations with unique intercepts for each cluster of plots.

Discussion

Results of this study supported earlier research findings that relative stand density is a significant factor that affects stand growth after thinning in Allegheny hardwoods (Roach 1977; Marquis et al. 1992; Marquis 1994; Nowak 1996). Moreover, results also indicated that current guidelines for prescribing thinning treatments (Marquis et al. 1992) are adequate for this forest cover type in the central Appalachians. For example, current recommendations for thinning 60-year-old stands include leaving a residual stand between 60 and 70% RD. In this study, net cubic volume growth, an appropriate measure of total merchantable volume growth, peaked at 70% RD (Fig. 4).

Results also supported findings that residual stand structure is a significant factor that affects growth and that current guidelines for distributing the cut are adequate in the central Appalachians. Marquis and Ernst (1991) determined that growth was maximized after a form of free thinning, where trees were removed from a range of sizes, with most of the cut taken from subordinate crown classes. The current recommendation is to distribute the cut such that three-fourths of the cut RD is from trees smaller than the medial stand diameter (Marquis et al. 1992). In this study, net sawtimber volume growth peaked where 78% of the cut was from trees smaller than the medial stand diameter (Fig. 7). Distributing the cut as recommended allows free growing space to be allocated to overstory trees that have the potential to immediately produce additional merchantable volume. Heavy cutting among overstory trees allocates growing space to small trees that take many years to become merchantable, and heavy cutting among understory trees does not reduce the competition for light that limits the growth of the larger merchantable trees (Marquis and Ernst 1991).

This study was conducted in 60-year-old Allegheny hardwoods, and RD after thinning increased by an average of 1.5% per year in plots thinned to 60% RD (Fig. 8). Roach (1977) also observed that RD increased by 1.5% per year after thinning in 50-year-old stands. Similarly, results from this study and those reported by Roach (1977) indicate that mortality

Table 7. Regression parameters from sawtimber volume growth equations.

(*a*) Regression parameters from sawtimber volume growth equations fit to data combined for all plots.

Dependent variable	n	Regression coefficient b_0	b_1	b_2	$S_{y,x}$	R^2
Net growth	21	569.64	–01909	–0.000 239	75.23	0.01
Ingrowth	21	83.09	3.2492	–0.024 018	79.60	0.04
Survivor growth	21	501.79	–3.8700	0.027 066	79.24	0.04
Mortality	21	15.24	–0.4299	0.003 300	7.57	0.08
Gross growth	21	584.88	–0.6208	0.003 048	77.01	0.01

Note: Model: $y = b_0 + b_1$ RD + b_2 RD^2 + e, where y is sawtimber volume (bd ft·acre^{-1}·year^{-1}), b is estimated regression coefficients, RD is relative density, and e is error (1 bd. ft./acre = 0.014 m^3/ha).

(*b*) Regression parameters from sawtimber volume growth equations with equal slope and unique intercept for each cluster.

Dependent variable	n	Regression coefficient b_{10}	b_{20}	b_1	b_2	$S_{y,x}$	R^2
Net growth	21	533.14	578.14	0.3986	–0.004 682	73.41	0.98
Ingrowth	21	14.16	99.15	4.3626	–0.032 410	67.51	0.90
Survivor growth	21	531.44	494.87	–4.3490	0.030 676	79.06	0.96
Mortality	21	12.46	15.89	–0.3850	0.002 949	7.55	0.26
Gross growth	21	545.60	594.03	0.013617	–0.001 733	74.71	0.99

Note: Model: $y = b_{i0} + b_1$ RD + b_2 RD^2 + e, where y is sawtimber volume (bd ft·acre^{-1}·year^{-1}), b is estimated regression coefficients, i is cluster, RD is relative density, and e is error (1 bd. ft./acre = 0.014 m^3/ha).

(*c*) Regression parameters from sawtimber volume growth equations with unique slope and intercept for each cluster.

Dependent variable	n	Regression coefficient b_{10}	b_{20}	b_{11}	b_{21}	b_{12}	b_{22}	$S_{y,x}$	R^2
Net growth	21	508.89	661.44	0.6761	–1.6314	–0.003 331	0.005 687	76.99	0.99
Ingrowth	21	104.26	20.08	1.1749	7.0038	–0.007 411	–0.051 586	70.13	0.91
Survivor growth	21	427.59	632.21	–1.1074	–8.3759	0.007 881	0.056 657	82.72	0.97
Mortality	21	22.96	–9.15	–0.6085	0.2593	0.003 802	–0.000 615	7.34	0.38
Gross growth	21	531.85	652.29	0.0676	–1.3720	0.000 471	0.005 071	78.87	0.99

Note: Model: $y = b_{i0} + b_{i1}$ RD + b_{i2} RD^2 + e, where y is sawtimber volume (bd ft·acre^{-1}·year^{-1}), b is estimated regression coefficients, i is cluster, RD is relative density, and e is error (1 bd. ft./acre = 0.014 m^3/ha).

becomes serious once RD exceeds 80% (Fig. 4). The implication of these results is that RD is not static after thinning, and it increases at a predictable rate so that forest managers can schedule subsequent silvicultural treatments about 15 to 20 years after thinning to minimize mortality due to overcrowding.

Roach (1977) found it difficult to change the proportion of the cherry–ash–poplar species group by more than 10% by thinning. Results from this study also indicated that species composition is not greatly altered by thinning, particularly when cut trees are distributed throughout a range of size classes. This general result makes it possible for managers to use pretreatment conditions such as species composition to categorize stands, and to prescribe appropriate treatments based on their expected growth response to changes in RD.

Pretreatment species composition affected the optimal level of RD, as observed in other thinning studies (Leak 1981; Nowak 1996). Periodic sawtimber volume production (harvested volume plus ending volume) peaked at 62% RD for plots with a relatively high proportion of black cherry, and 48% for plots with less black cherry (Fig. 6). Although slope coefficients between plots in clusters A and B were not significantly different (Table 4), the regression equations with unique slopes and intercepts also revealed slight differences in optimal RD points related to species composition for net cubic volume growth (Table 6*c*). Nowak (1996) observed that as the proportion of black cherry increased in Allegheny hardwood stands, the RD for maximum net cubic volume growth also increased. Roach (1977) alluded to this phenomenon in recommending that stands 60 or more years old should not be thinned below 70% RD, unless the residual stand contained a high proportion of shade-tolerant species. Canham (1988) and Ellis (1979) described the capacity of such shade-tolerant species to expand their crowns and exhibit greater responses to reductions in density compared with shade-intolerant species like black cherry.

Different optimal RD levels due to species composition may not have serious practical implications, because growth curves change gradually over the range of recommended thinning treatments and it may be difficult to achieve exact RD targets in the field. In addition, thinning prescriptions are based on average stand conditions, yet species composition and stand density often vary within a stand.

Species composition also affected net growth at each level of RD. Intercept coefficients differed for plots in clusters A and B (Table 4), indicating that net growth was greater for plots in cluster B than in cluster A. Cluster B included plots with more dense shade-tolerant understories and lower proportions

Fig. 5. Sawtimber volume growth as a function of RD for regression equations with equal slope and unique intercept.

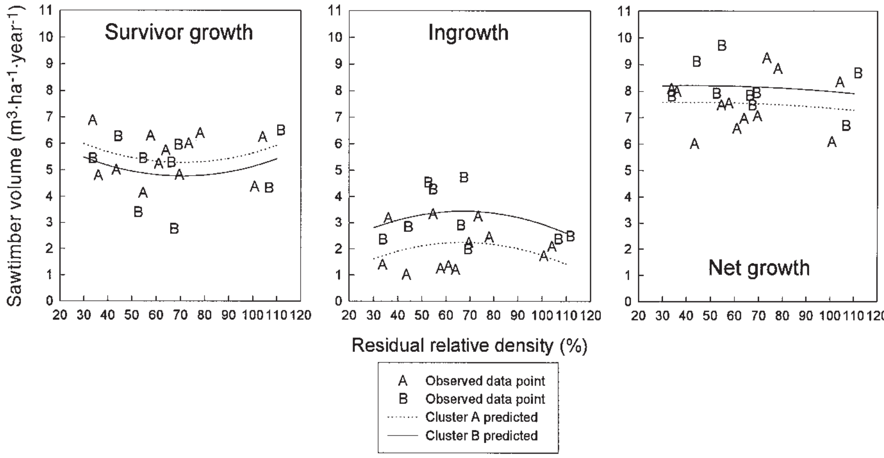


Fig. 6. Periodic sawtimber volume production (cut plus ending volume) as a function of RD.

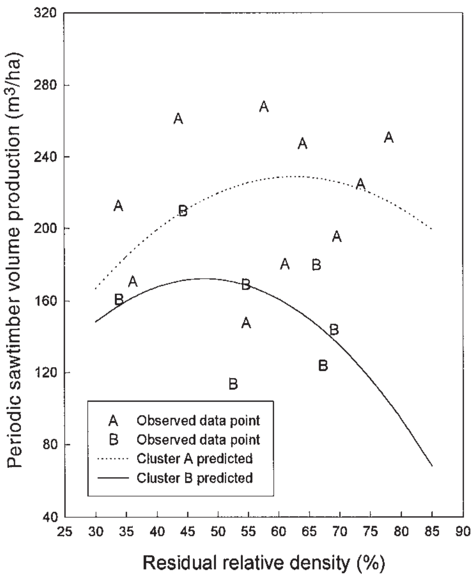
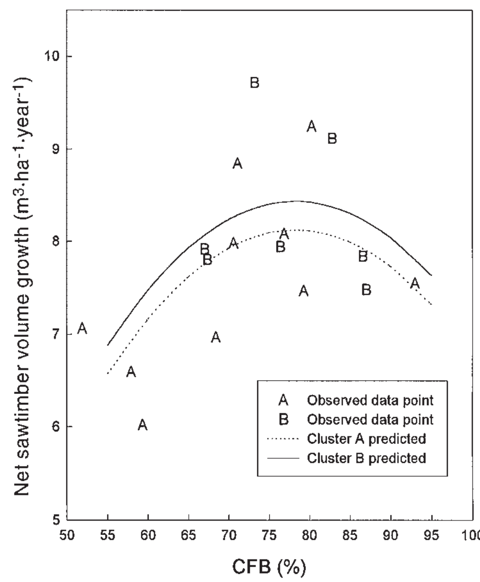


Fig. 7. Net sawtimber volume growth as a function of the percentage of RD cut from below (CFB) the stand medial diameter.



of black cherry. For basal area and cubic volume growth, plots in cluster B exhibited greater response of trees in subordinate crown classes as described by Canham (1988) and Ellis (1979) and greater survivor growth than plots in cluster A (Figs. 3 and 4). For sawtimber volume growth, ingrowth was more important than survivor growth. For example, the initial DBH of black cherry averaged 28.7 and 25.4 cm for plots in clusters A and B, respectively (Table 3). This trend continued after thinning, and sawtimber volume survivor growth was slightly greater for plots in cluster A. However, plots in cluster B had greater sawtimber ingrowth as numerous poletimber trees grew into the sawtimber size class (Fig. 5), resulting in greater net growth for plots in cluster B.

Grouping plots according to pretreatment species composition and analyzing growth response based on continuous variation of RD using regression analyses disclosed some important issues that may affect how the results of thinning trials are interpreted. For example, Lamson and Smith (1988) did not account for plot variation by pretreatment species composition and compared 5-year net growth responses at discrete levels of RD on the same plots used for this study. They concluded that growth was essentially constant from 45 to 75% RD. Results of other studies also have concluded that stand growth response after thinning is constant over a relatively wide range of RD (Solomon 1977; Marquis 1986; Ernst 1987). The analysis of 10-year growth response in this study revealed that net basal area growth peaked at 52% RD (Fig. 3), net cubic volume growth peaked at 70% RD (Fig. 4), and net sawtimber volume growth peaked at 43% RD (Fig. 5). Grouping plots with similar pretreatment characteristics accounted for some plot variation that may have masked the effect of RD in the earlier analyses. In addition, growth response data were fit with quadratic models, which indicated certain minimum and maximum points for each growth component.

Thinning treatments stimulated diameter growth of the species in subordinate crown classes greater than that of the codominant black cherry. The maples and American beech used the additional site resources after thinning to more than double

Table 8. Comparison of 10-year DBH (cm) growth by thinning treatment for each species.

			Unweighted		Weighted		
Relative density	Plots (n)	Initial DBH	DBH growth	SE	DBH growth*	SE	HSD†
Black cherry							
44	5	31.0	4.821	0.117	4.663	0.107	*a*
58	6	29.5	4.161	0.099	4.148	0.089	*b*
69	6	28.4	3.495	0.081	3.571	0.074	*c*
106	4	29.2	2.736	0.094	2.748	0.084	*d*
Red maple							
44	5	12.2	3.373	0.114	3.351	0.079	*a*
58	6	13.2	2.908	0.089	2.865	0.061	*b*
69	6	14.2	2.583	0.094	2.380	0.066	*b*
106	4	12.4	1.265	0.086	1.387	0.058	*c*
Sugar maple							
44	5	6.4	3.340	0.135	3.495	0.107	*a*
58	6	7.4	1.778	0.086	1.793	0.069	*b*
69	6	7.1	1.267	0.081	1.323	0.066	*c*
106	4	8.4	0.500	0.076	0.389	0.061	*d*
American beech							
44	5	4.3	2.789	0.074	2.779	0.069	*a*
58	6	4.6	2.098	0.056	2.045	0.051	*b*
69	6	4.3	1.483	0.048	1.461	0.046	*c*
106	4	3.8	0.455	0.064	0.564	0.058	*d*

*Weighted by initial DBH.

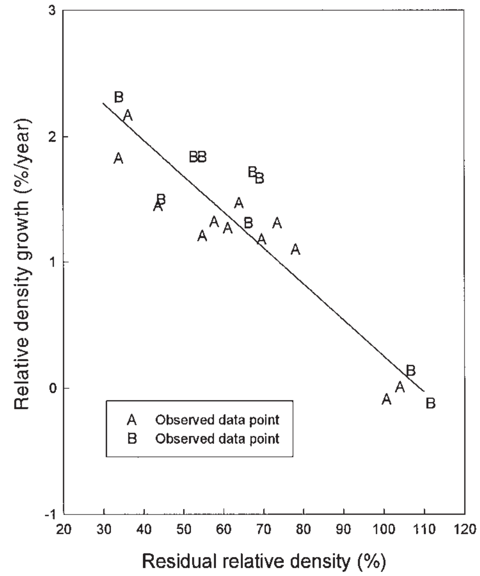
†For each species, rows followed by the same letters are not significantly different, $P > 0.01$, based on Tukey–Kramer honestly significant difference test (HSD).

their diameter growth rates compared with controls (Table 8), while thinning increased black cherry diameter growth by 76% compared with controls. One explanation for this response is that light usually is the limiting site resource affecting hardwood growth (Kelty et al. 1987; Marquis and Ernst 1991), and trees in subordinate crown positions receive proportionately more of the light resources freed by thinning than trees already in a codominant crown position before thinning. Another factor is that trees in subordinate crown classes were shade tolerant. Nowak (1996) discussed the role of crown architecture and branching characteristics as a possible explanation for varying growth response among species of different shade tolerance after thinning.

While RD and stand structure are significant factors that affect stand growth, the degree of crown release also is a significant factor that affects the growth of individual trees that contribute to stand growth. Recent studies indicated that DBH growth of individual trees was related to the degree of crown release resulting from the cut (Lamson et al. 1990; Perkey et al. 1994; Smith et al. 1994). For example, 5-year DBH growth averaged 2.95 cm for codominant black cherry trees after a full crown release and 1.70 cm for similar trees released on only one side after thinning (Smith et al. 1994). Thus, thinning treatments based solely on RD and stand structure can leave some individual trees with only a partial crown release, and these trees may not grow at their maximum rate after thinning.

Lamson et al. (1990) suggested that one way to improve the

Fig. 8. Annual RD growth as a function of residual RD.



overall effectiveness of thinning treatments is to merge the concepts of RD and stand structure (Roach 1977) with the concept crown release on individual crop trees (Perkey et al. 1994). Crop tree management is an innovative thinning method that is designed to focus site resources on selected residual trees (crop trees) that best meet management objectives (Perkey et al. 1994). This method entails removing adjacent competing trees so that the crowns of the designated crop trees are properly released after thinning. Recent recommendations for crop-tree release thinnings recognized the importance of controlling both stand-level and individual-tree-level competition to improve the overall stand response to thinning (Lamson et al. 1990; Perkey et al. 1994; Smith et al. 1994). Perkey et al. (1994) recommended the use of trial marking on fixed-area plots to adjust the target number of crop trees per unit area, stressing that all crop trees should receive a full crown release, and that the intensity of the cut should be adjusted by altering the number of crop trees, not the degree of release for each crop tree. In this study, the residual stand contained 146 and 116 sawtimber trees/ha in plots thinned to 75 and 45% RD, respectively (Table 2). Thus, a reasonable starting point for trial marking to achieve recommended RD levels in 60-year-old Allegheny hardwoods is to select about 130 crop trees/ha.

Although RD, stand structure, and crown growing space have been shown to affect growth as measured by certain criteria, additional research is needed to analyse the interaction and relative impact of these factors on overall stand response to thinning. This research should define how crown release treatments affect the distribution of the cut and residual stand structure, how crown growing space affects the trade-off between faster growth and quality of individual trees, and how field procedures can be simplified so that stand-level and tree-level competition are in proper balance.

In summary, results from this study supported current recommendations developed by Roach (1977) and updated by Marquis et al. (1992) for thinning Allegheny hardwoods for wood production. Moreover, results indicated that these guidelines

Table 9. Regression parameters from DBH growth equations.

(*a*) Regression parameters from DBH growth equations fit using pooled data from both clusters of plots.

		Regression coefficient				
Species	*n*	b_0	b_1	b_2	$S_{y,x}$	R^2
Black cherry	910	1.066	0.102	–0.011	0.504	0.37
Red maple	1356	1.072	0.185	–0.014	0.457	0.63
Sugar maple	679	1.142	0.138	–0.014	0.383	0.54
American beech	1354	1.207	0.233	–0.014	0.371	0.48

Note: Model: $y = b_0 + b_1$ DBH + b_2 RD + e, where y is 10-year DBH growth in inches, b is estimated regression coefficients, DBH is initial DBH, RD is relative density, and e is error (1 in. = 2.54 cm).

(*b*) Regression parameters from DBH growth equations with equal slope and unique intercept for each cluster.

		Regression coefficient					
Species	*n*	b_{10}	b_{20}	b_1	b_2	$S_{y,x}$	R^2
Black cherry	910	0.725	1.034	0.121	–0.012	0.482	0.91
Red maple	1356	1.041	1.186	0.185	–0.015	0.452	0.86
Sugar maple	679	1.148	1.117	0.138	–0.013	0.384	0.76
American beech	1354	1.174	1.230	0.232	–0.014	0.370	0.80

Note: Model: $y = b_{i0} + b_1$ DBH + b_2 RD + e, where y is 10-year DBH growth in inches, b is estimated regression coefficients, i is cluster, DBH is initial DBH, RD is relative density, and e is error (1 in. = 2.54 cm).

are applicable for thinning similar stands in the central Appalachian region. Thinning to 70% RD as recommended for 60-year-old stands maximized net cubic volume growth. Sawtimber volume production peaked between 48 and 62% RD, increasing as the proportion of black cherry increased. Net sawtimber volume growth peaked where 78% of the cut RD was in trees smaller than the medial stand diameter.

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