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by George R. Trimble, Jr.

U.S. FOREST SERVICE RESEARCH PAPER NE-98
1968

NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA.
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE
RICHARD D. LANE, DIRECTOR

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The Author

GEORGE R. TRIMBLE, JR. is a project leader in timber-management research for the Northeastern Forest Experiment Station. He is located at the Station's Timber and Watershed Laboratory at Parsons, West Virginia. He received his Bachelor's degree in forestry from the University of Maine, and has done graduate work at Duke University in forest soils. Mr. Trimble joined the U. S. Forest Service in 1932. He worked for a number of years in watershed-management research both in West Virginia and New Hampshire, and has worked on forest-management problems throughout the Northeast.

INTRODUCTION

THE MANIPULATION of stand density is one of the primary tools that foresters use to regulate tree growth. By reducing stand density, it is possible to stimulate the growth of the residual trees and concentrate the volume on a smaller number of more valuable trees. Total stand volume production is not greatly affected by this procedure as long as density is not reduced below the point where the trees fully occupy the site.

Proper regulation of growth requires a thorough knowledge of the effect of varying densities on stand behavior. How low can density be dropped without reducing total volume production? How much is individual tree growth stimulated by reduced density? What effect does site have on the choice of stand density?

To answer these questions for Appalachian hardwoods, a study was made to determine the effect of varying residual basal area on subsequent stand growth. An excellent site and a fair one were selected for the study.

THE STUDY

Description of Area

The study was conducted in undisturbed hardwood stands on the Fernow Experimental Forest near Parsons, West Virginia. Though most of the trees were 48-year-old second-growth, there were a number of scattered old-growth stems that were left from the previous logging in the virgin timber.

Species composition varied between the sites studied. On the excellent site, yellow-poplar (*Liriodendron tulipifera* L.), black cherry (*Prunus serotina* Ehrh.), northern red oak (*Quercus rubra* L.), and sugar maple (*Acer saccharum* Marsh.) predominated. Other species in mixture were white ash (*Fraxinus americana* L.), beech (*Fagus grandifolia* Ehrh.), basswood (*Tilia americana* L.), cucumbertree (*Magnolia acuminata* L.), black locust (*Robinia pseudoacacia* L.), hickory (*Carya sp.* Nutt.), and red maple (*Acer rubrum* L.),

The fair site was characterized by chestnut oak (*Quercus prinus* L.), red oak, white oak (*Quercus alba* L.), scarlet oak (*Quercus coccinea* Muenchh.), red maple, black locust, black gum (*Nyssa sylvatica* Marsh.), and sassafras (*Sassafras albidum* (Nutt.) Nees).

These differences in species composition between the two sites are typical of those between other similar sites throughout the Appalachian hardwood region. The better sites characteristically have a higher proportion of the more valuable and faster growing species. Within each site, species composition was relatively uniform so that differences in the proportion of fast-growing species on a plot should have had little effect on the study results. The one possible exception to this is that the high-density plots on the excellent site had a lower proportion of the fast-growing red oak and yellow-poplar than did the other four plots on the same site.

Another characteristic difference between the two sites was that trees of equal diameter had greater merchantable heights on the better site (table 6, appendix). Thus a given increase in diameter resulted in a proportionately larger volume increase on the better site.

While the second-growth was relatively even-aged, it contained a wide range in diameter classes. This is typical of mixed stands of Appalachian hardwoods (*Gibbs 1963*).

Located at an elevation of nearly 3,000 feet, this area is subjected to a rather cool climate. The frost-free growing season is 130 to 140 days and the average temperature is 48° Fahrenheit. Average annual rainfall is about 60 inches and is fairly well distributed throughout the year. Snowfall is heavy in the winter. The soils are medium-textured and are well-drained.

Methods

In 1954, twelve 2½-acre plots were laid out; six of them were located on an excellent site — about site index 85 for oak — and six on a fair site — about site index 63 for oak — (*Schnur 1937; Trimble and Weitzman 1956*). The areas were well stocked before cutting (table 1).

The plots were marked for cutting to specified basal areas to obtain a comparison of growth rates by sites and stocking levels. Three residual basal areas in trees over 5.0 inches d.b.h. were chosen for each site, and replicated plots were marked accordingly. For the better site, residual basal areas were 100, 80, and 60 square feet. For the poorer site, the levels were 75, 60, and 45 square feet. These levels were based on local experience as well as literature review, and were chosen to represent a reasonable range of residual stocking. Cutting resulted in only slight variations from the specified levels (table 1).

Basal area in trees over 5 inches d.b.h. is used as the expression of stand density throughout this paper. Other expressions, such as basal area in trees over 11 inches d.b.h., were also tested, but results were similar in all cases.

Table 1.—The initial stand

Density	D.b.h.	Basal area[1]	Cubic volume	Board volume[2]
	Inches	*Square feet per acre*	*Cubic feet per acre*	*Board feet per acre*
		BEFORE CUTTING		
Excellent site:				
High	11.3	134	3,510	14,900
Medium	11.4	133	3,480	14,900
Low	11.6	130	3,420	15,100
Fair site:				
High	10.3	93	2,070	8,500
Medium	9.0	92	1,900	5,400
Low	9.0	90	1,910	5,600
		AFTER CUTTING		
Excellent site:				
High	10.8	100	2,570	10,100
Medium	10.6	80	2,050	7,800
Low	10.0	59	1,490	5,200
Fair site:				
High	9.9	72	1,560	5,800
Medium	10.0	59	1,260	4,100
Low	9.6	46	970	3,200

[1] See table 7 for breakdown of residual basal area by size classes.
[2] Volume to an 8-inch top inside bark as determined by the International 1/4-inch kerf rule.

To leave a distribution of size classes typical of local unmanaged second-growth stands, cutting was done throughout the range of tree diameters above 9.0 inches d.b.h. In essence, the old residuals were removed and the plots were thinned at different intensities throughout the stand structure by this operation. To guide the distribution of stem sizes to be left, a "Q" of 1.6 was chosen since it was found to be typical of unmanaged hardwood stands in the area. "Q" is the quotient of number of trees in a 2-inch d.b.h. class divided by the number in the next larger class (*Meyer 1952*).

One-hundred-percent inventories of trees over 5.0 inches d.b.h. were made at 2-year intervals throughout the 10-year study period. A 10-percent systematic sample was taken of stems 1 to 5 inches d.b.h. on 1/100-acre plots.

After 10 years, a random sample of butt log grades was taken — using standard Forest Service factory-log grades (*Ostrander 1965*) — on the sawlog trees. In addition, epicormic branching by 8-foot bole sections was recorded on every fifth tree over 5.0 inches d.b.h. These observations provided a basis for judging the effect of treatment on log quality.

Four types of growth were studied: (1) cubic volume, (2) board-foot volume, (3) basal area, and (4) diameter. Growth calculations were based on the first 10 years after cutting. Cubic volume, based on a local volume table, was computed to a 4-inch top inside bark for all trees over 5.0 inches d.b.h. Board-foot volume, based on a local volume table, was computed to an 8-inch top inside bark (or to where the stem split up into crown) for all trees over 11.0 inches d.b.h.

Statistical testing of growth differences due to site or residual stand density was done through regression analysis.

RESULTS

Cubic-Volume Growth

Annual net cubic-volume growth of the merchantable stand did not appear to be related to residual stand density (table 2). However, when this growth was broken down by stand segments (growth on trees 5 to 11 inches d.b.h. and on trees 11 inches

Table 2.—Annual cubic-volume growth, in cubic feet per acre per year

Density	Accretion	Net growth	Ingrowth	Mortality
		EXCELLENT SITE		
High	90.6	93.2	8.0	5.4
Medium	91.6	96.6	10.0	5.0
Low	83.7	91.7	12.5	4.5
All densities	88.6	93.8	10.2	5.0
		FAIR SITE		
High	51.2	59.8	9.3	.7
Medium	56.0	66.5	19.2	8.8
Low	52.9	70.2	19.0	1.7
All densities	53.3	65.5	15.9	3.7

d.b.h. and larger), there were significant relationships with density, as follows:

	Trees 5 inches to 11 inches d.b.h.	*Trees more than 11 inches d.b.h.*
Excellent site:		
High density	—15	109
Medium density	—4	100
Low density	5	87
Fair site:		
High density	10	50
Medium density	12	55
Low density	19	51

Cubic-volume growth of the smaller trees (5 to 11 inches d.b.h.) increased at the lower densities. These differences were significant at the 5-percent level on the excellent site and at the 10-percent level on the fair site. In contrast, cubic-volume growth of the larger trees (11 inches and larger d.b.h.) decreased significantly (5 percent level) at the lower densities on the excellent site, although there was no such relationship on the fair site.

Ingrowth across the 5-inch threshold was generally greatest at the lower densities. However, differences large enough to attain statistical significance (5-percent level) occurred only on the fair site between the high density and the other two densities. There were no significant differences in mortality.

Cubic-foot growth percent (net growth expressed as a percentage of the initial volume) increased significantly (5-percent level) with decreasing density on both sites. Growth percent on the excellent site averaged 3.8 percent on the high-density plots as compared with 6.5 percent on the low-density plots. Corresponding figures for the fair site were 3.9 and 7.4 percent respectively.

Cubic-foot volume growth was significantly (5-percent level) higher on the better site. For all trees 5 inches d.b.h. and larger, net growth was 1.4 times larger and accretion was 1.7 times larger on the excellent site than it was on the fair site.

Board-Foot Volume Growth

Annual net board-foot volume growth of the merchantable stand was significantly (10-percent level) related to density on

Table 3.—Annual board-foot volume growth, in board feet per acre per year

Density	Accretion	Net growth	Ingrowth	Mortality
		EXCELLENT SITE		
High	462	681	219	0
Medium	450	656	206	0
Low	360	544	184	0
All densities	424	627	203	0
		FAIR SITE		
High	188	295	107	0
Medium	136	310	188	14
Low	142	293	151	0
All densities	156	299	149	5

the excellent site (table 3). The low-density treatment had significantly less board-foot growth than the other two densities. No relationship was found between density and board-foot growth on the fair site.

Board-foot growth percentage increased significantly (5-percent level) with decreasing density on both sites. Growth percent on the excellent site averaged 6.8 percent on the high-density plots and 10.2 percent on the low-density plots. Corresponding figures for the fair site were 5.6 and 9.0 percent respectively.

Board-foot volume growth was significantly higher (5-percent level) on the better site. Net growth was 2.1 times larger and accretion was 2.7 times larger on the excellent site than it was on the fair site.

Basal-Area Growth

Net basal-area growth in trees over 5 inches d.b.h. showed no relationship to stand density. However, when this growth was broken down by stand segments, there were significant relationships (table 4). Basal-area growth in small trees (5 to 11 inches d.b.h.) increased with the lower stand densities; these differences were significant at the 5-percent level on both sites. In contrast, basal-area growth of the larger trees (11 inches and larger d.b.h.) decreased significantly (5-percent level) at the

Table 4.—Annual net basal-area growth, in square feet per acre per year

Density	Tree size, d.b.h. 5 to 11 inches	More than 11 inches	Total
	EXCELLENT SITE		
High	—0.6	3.8	3.1
Medium	—.2	3.4	3.3
Low	.3	3.0	3.3
All densities	—.2	3.4	3.2
	FAIR SITE		
High	.5	1.9	2.4
Medium	.6	2.2	2.9
Low	1.0	2.0	3.1
All densities	.7	2.0	2.7

lower densities on the excellent site. There was no such relationship with the larger trees on the fair site.

Basal-area growth was higher on the better site for total trees and for the larger trees. Basal-area growth of small trees was higher on the fair site because of the lighter overstory.

Diameter Growth

Diameter growth rates were computed separately for each of the three most numerous species on each site. On the excellent site, red oak grew faster than yellow-poplar, which in turn grew faster than black cherry. These differences were significant at the 5-percent level (table 5). Red oak also responded more to differences in release than did yellow-poplar. Black cherry apparently did not respond to release at all. On the fair site, there were no significant differences between the three most numerous species, although the trend of decreasing growth from red oak to chestnut oak to white oak was in line with a previous report (*Trimble 1960*). Early growth of these species on both sites in the undisturbed stands had apparently been similar since there were no significant differences in initial diameters.

Diameter growth of the residual trees was significantly (5-

Table 5.—Ten-year diameter growth, in inches, of three most numerous species on each site — sawtimber trees only, more than 11 inches d.b.h.

Density	Yellow-poplar	Black cherry	Red oak	Chestnut oak	White oak	All species[1]	All species[1] more than 5 inches d.b.h.
			EXCELLENT SITE				
High	2.4	1.7	2.9	—	—	2.2	1.4
Medium	2.5	2.1	3.3	—	—	2.6	1.6
Low	2.7	1.9	3.9	—	—	2.8	1.8
			FAIR SITE				
High	—	—	1.7	1.6	1.6	1.8	1.2
Medium	—	—	2.0	1.8	1.9	1.8	1.5
Low	—	—	2.5	2.2	1.5	2.4	1.9

[1] Includes growth of all trees present, regardless of species.

percent level) greater at the lower stand densities on both sites (table 5).

Because of greater ingrowth at the lower densities, average stand diameter was not greatly affected by stand density. Average stand diameters on the excellent site of 10.0, 9.9, and 9.4 inches for the high-, medium-, and low-density plots respectively had increased to only 11.0, 10.8, and 10.2 inches after 10 years. Similar figures for the fair site were 9.0, 9.0, and 8.9 inches immediately after cutting and 9.6, 9.2, and 9.0 inches after 10 years.

Diameter growth was significantly higher on the better site. The diameter growth rate of red oak, the one species common to both sites, was 1.6 times larger on the excellent site than it was on the fair site.

Log-Quality Changes

Butt-log grade comparisons made at the end of the study showed no important quality differences attributable to treatments. Epicormic branching comparisons made by species and crown-class likewise revealed no important differences due to density for red oak and yellow-poplar on the excellent site. It appeared that epicormic branching increased at the lower stand densities on black cherry — but only on the stem above 32 feet; i.e., above the first two logs.

On the fair site, comparisons of epicormic branching on the first two logs revealed no treatment effects for white oak, red oak, and chestnut oak (the only species sampled in sufficient numbers for testing). There were not enough samples with more than two logs to make valid comparisons above 32 feet on the fair site.

It should be recognized that epicormic branching differences might possibly have shown up a few years after cutting and the branches might have died and fallen off because of increasing stand density before the 10-year observations.

DISCUSSION

The results of these experiments may be summarized briefly:

- Low stand densities produced the greatest growth of individual trees.
- Low stand densities favored the growth of the smaller trees in the stand; i.e., trees 5 to 11 inches d.b.h. and trees growing across the threshold diameter.
- Low stand densities reduced the total growth of the larger trees in the stand on the excellent site but had no effect on them on the fair site.
- Stand density had no effect upon total growth of the entire stand above 5 inches d.b.h.
- Stand density had no important effects on log quality.
- The excellent site produced considerably more growth than the fair site.

A landowner or manager interested in bulk products — where size and clear wood are not important considerations — could obtain about equal volume production from any of the densities tested. To maximize his return on investment (growth percentages on residual volume) he should utilize the lower densities: 60 square-foot residual basal area on the excellent site or 45 square-foot residual basal area on the fair site. If this production were to be maintained indefinitely through partial cuttings, it would be important to maintain about 15 square feet of basal area in the 1- to 5-inch d.b.h. class to provide for ingrowth.

However, it should be emphasized that the better sites would normally be devoted to growing veneer and sawtimber, and small products would be harvested only as byproducts.

A landowner or manager interested in sawtimber and veneer production on a fair site could also obtain about equal volume production and maximize his return on investment by cutting to 45 square feet of basal area. There would be little or no reduction in quality due to epicormic branching as long as he maintained 15 to 20 square feet of basal area in stems in the 1- to 5-inch d.b.h. class to shade the first two logs of larger stems.

However, on the better sites, the decision is more difficult. Residual stand density can be reduced to about 80 square feet of basal area without reducing board-foot growth and with no appreciable reduction in quality due to epicormic branching. Reducing residual basal area further would have several opposing effects in stands such as these: it would reduce total sawtimber production but it would increase individual tree growth rate and size and reduce the investment in growing stock. In cases where stands would be managed indefinitely by partial cuttings, it is recommended that residual density be held at 80 square feet of basal area per acre. In cases where even-aged management would be applied, it might be desirable to reduce density further, depending upon the desired rotation ages, value differentials attributable to larger size, etc.

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APPENDIX

Table 6.—Merchantable heights of sawtimber size trees, in feet

D.b.h. (inches)	Excellent site	Fair site
14	41	29
16	47	33
18	44	34
20	45	36
22	53	40

Table 7.—Residual basal area, by size classes, in square feet per acre

Density	Size class, d.b.h. 1 to 5 inches	5 to 11 inches	More than 11 inches	Total, more than 5 inches
		EXCELLENT SITE		
High	13.8	35.5	64.3	99.0
Medium	15.9	31.2	48.8	80.0
Low	13.7	26.2	33.2	59.4
		FAIR SITE		
High	17.6	30.4	41.9	72.3
Medium	16.1	29.4	29.4	58.8
Low	18.2	22.7	23.2	45.9