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The Influence of Stand Density and Structure on Growth of Northern Hardwoods in New England

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ABSTRACT

Growth of northern hardwoods over a 10-year period was studied in plots that were treated to produce residual densities of 40, 60, 80, and 100 square feet of basal area per acre with stand structures of 30, 45, and 60 percent sawtimber. Both diameter and basal area growth are tabulated by treatment and species.

THERE IS increased emphasis by landowners on intensive forest management, but the ability of a forest manager to make decisions for any stand of timber depends upon the growth information available to him. Regardless of the objectives—timber, aesthetics, recreation, water, or wildlife—the response of the residual stand depends on the treatment the stand receives. The residual density of a forest stand is the basis of silvicultural treatment, since density influences growth per acre. Therefore, management decisions that will result in maintaining the stand for different objectives can be made using residual stand density as a means of controlling growth response.

A study was established in a second-growth northern hardwood stand on the Bartlett Experimental Forest, Bartlett, N. H., to determine what average level of residual density will produce the best growth response. The stand originated from clearcutting 70 to 90 years ago and is composed primarily of beech, red maple, and paper birch, with some sugar maple and yellow birch, and a few white ash and miscellanous trees of other species.

METHODS

A total of 48 square 1/3-acre plots were laid out on a relatively uniform site. Each plot was surrounded by a 50-foot wide treated isolation strip.

Four levels of residual stand density were assigned at random to these plots: 100, 80, 60, and 40 square feet of basal area per acre in trees 4.5 inches dbh and larger. Within each level of residual stand density, three levels of residual stand structure were randomly assigned: 30, 45, and 60 percent sawtimber (trees 10.5 inches dbh and larger). The plot layout consisted of four plots with each of these 12 combinations, in a completely randomized design.

To bring stand structure to the level assigned to each plot, unwanted trees were frilled and treated chemically in the fall of 1963. Trees that were diseased or dying were removed first, and then trees were removed at random to meet the plot treatment specifications. Most plots were similar in species composition, but on a few plots some effort was made to make species composition similar to that of the total area (table 1). Trees that did not die were re-treated

Table 1.—Initial species composition on study plots (in percent)

Treatment		Species								
Residual basal area	Percent Sawtimber	Beech	Yellow birch	Sugar maple	Red maple	Paper birch	White ash	Red spruce	Hemlock	Other
ft^2/acre	30	25.6	10.0	—	32.3	23.7	.8	—	7.6	—
40	45	24.3	3.4	4.5	26.0	21.4	7.5	—	12.9	—
	60	39.0	7.8	5.5	21.8	19.1	1.0	—	5.5	.3
	All	29.6	7.1	3.3	26.7	21.4	3.1	—	8.7	.1
	30	51.7	12.5	6.0	6.5	10.4	7.5	1.0	4.4	—
60	45	37.5	11.1	3.7	21.3	19.0	.7	—	6.7	—
	60	14.7	3.8	5.5	37.7	28.9	—	—	9.4	—
	All	34.7	9.2	5.1	21.7	19.4	2.7	.4	6.8	—
	30	23.0	9.3	6.6	35.4	14.0	2.0	—	9.4	.3
80	45	36.5	6.4	8.6	16.0	27.3	.9	1.1	3.2	—
	60	35.2	12.0	11.6	16.3	12.6	5.3	1.7	5.3	—
	All	31.6	9.2	8.9	22.6	18.0	2.7	.9	6.0	.1
	30	8.4	4.1	3.5	45.3	23.5	1.2	.4	10.1	3.5
100	45	36.4	13.7	1.0	22.8	17.8	—	.2	8.1	—
	60	21.7	9.4	11.1	34.4	14.7	1.8	.5	6.4	—
	All	22.1	9.1	5.2	34.2	18.6	1.0	.4	8.2	1.2

in the spring of 1964. Initial diameter measurements and marking were done after the growing season of 1964, and a few frilled trees that remained alive were cut to complete the treatments.

All trees on the 1/3-acre plot were recorded by species and measured to the nearest 0.1 inch; each tree was numbered and the point of diameter measurement (usually 4.5 feet) was marked with paint. Plots were reinventoried 3, 5, 8, and 10 growing seasons after installation. Reproduction information was taken after 9 growing seasons *(Leak and Solomon 1975)*.

Basal area growth was averaged for the four plots that received each treatment and then placed on an annual basis for comparison with gross growth, production, accretion, ingrowth, and mortality. A stepwise regression analysis was used to develop relationships between these dependent growth measures and the residual basal area and percentage of sawtimber in the stand. The independent variables were residual basal area, residual basal area squared, percent sawtimber, percent sawtimber squared, and the interaction of residual basal area and percent sawtimber. The interaction of basal area and percent sawtimber is the same as the residual basal area in sawtimber. It is given because the residual basal area in sawtimber was not used as an independent variable.

Both diameter growth and basal area growth were analyzed by species and size class for the different treatments. The diameter growth per tree was computed on an annual basis by species for each treatment. The diameter growth per tree was then computed separately for survivor trees, ingrowth trees, and trees that died during the study.

BASAL AREA GROWTH

The terms used in this paper have been previously defined by others *(Erdmann and Oberg 1973; Forbes 1955; Blum and Filip 1963; Gilbert 1954; Beers 1962; Marquis and Beers 1969; Frayer 1967)*.

Survivor growth—Increase in basal area of trees present at both inventories.

Accretion—Increase in the basal area of all trees present at the initial inventory, plus ingrowth accretion. This includes accretion on trees in the survivor, ingrowth, and mortality groups *(Frayer 1967)*.

Ingrowth—Trees that grew larger than the threshold size (4.5 inches) between inventories.

Mortality—Trees that died during the period (including ingrowth).

Production—(Net increase)—The net change in basal area between two inventories (accretion + ingrowth - mortality).

Gross growth—Total basal area produced by all trees during the period (production + mortality).

Gross Growth

Average annual gross growth in basal area remained relatively constant over a range of treatments based on residual basal area and size class (table 2). This was true also in other studies of northern hardwoods, both in the Northeast *(Blum and Filip 1963; Solomon and Leak 1969; Mar:Moller 1947)* and in the Lake States *(Church 1960; Erdmann and Oberg 1973; Eyre and Zilligitt 1953)*.

There is a slight decline in gross growth as both residual basal area and the percentage of sawtimber increase. More open stands of smaller trees apparently produce higher rates of gross basal area growth than more densely stocked stands of larger trees. This additional growth may occur because stands in the lower residual densitites do not fully utilize the site, and thus leave space for greater annual growth. Or the greater basal area growth of poletimber may not mean greater growth in volume.

Production

The average annual basal area production per acre for the total stand decreased as residual basal area per acre increased and as the percentage of sawtimber in the stand increased (table 2). Studies in both New England and the Lake States have indicated that production decreases as residual basal area increases. The total production of an approximately balanced stand of pole and sawtimber is 1.2 square feet annually for 100 square feet of basal area. This agrees with work by Church *(1960)* and with work by Leak *(1961)* in younger stands. However, Jensen *(1941)* and Blum and Filip *(1963)*, working in slightly older stands, found production to be 2.3 square feet annually. Blum and Filip *(1963)* and Church *(1960)* show an increase in production as residual basal area increases; Leak *(1961)* shows an increase to 2.3 square feet for the lowest den-

Table 2.—Average annual gross growth, production, accretion, ingrowth, and mortality by size class and treatment (in square feet of basal area per acre)

Residual basal area	Percent sawtimber [a]	Gross growth	Production			Accretion			Ingrowth		Mortality		
			Poletimber	Sawtimber	Stand Total	Poletimber	Sawtimber	Stand Total	Poletimber	Sawtimber	Poletimber	Sawtimber	Stand Total
40	30	2.73	0.79	1.43	2.22	1.39	0.51	1.90	0.83	1.17	0.26	0.25	0.51
	45	2.58	.67	1.33	2.00	1.10	.68	1.78	.80	.90	.33	.25	.58
	60	2.59	1.33	.51	1.84	1.10	.69	1.79	.80	.40	.16	.59	.75
60	30	2.38	.40	1.31	1.71	1.35	.55	1.90	.48	1.04	.39	.28	.67
	45	2.51	.63	1.66	2.29	1.16	.76	1.92	.59	.90	.22	—	.22
	60	2.33	.40	1.61	2.01	.88	.88	1.76	.57	.86	.20	.12	.32
80	30	2.18	-.26	1.95	1.69	1.31	.64	1.95	.23	1.31	.49	—	.49
	45	2.13	.05	1.62	1.67	1.11	.71	1.82	.31	1.13	.24	.22	.46
	60	1.94	.20	.95	1.15	.70	.92	1.62	.32	.59	.24	.55	.79
100	30	2.45	-.11	1.85	1.74	1.32	.70	2.02	.43	1.40	.46	.25	.71
	45	2.16	-.36	1.57	1.21	1.01	.83	1.84	.32	1.22	.47	.48	.95
	60	1.86	-.19	1.10	0.91	.62	1.07	1.69	.17	.50	.48	.47	.95

[a] Trees from 4.5 inches to 10.5 inches dbh were classified as poletimber; trees more than 10.5 inches dbh were classified as sawtimber.

Table 3.—Annual accretion by species, size class, and treatment (in square feet of basal area per acre)

Species	Size	Treatment 40			60			80			100		
		30	45	60	30	45	60	30	45	60	30	45	60
Beech	Poletimber	.42	.37	.37	.65	.48	.22	.36	.48	.28	.24	.45	.23
	Sawtimber	.10	.09	.19	.29	.27	.10	.09	.28	.32	.01	.27	.20
Sugar maple	Poletimber	—	.07	.04	.10	.04	.03	.05	.04	.06	.03	.01	.05
	Sawtimber	—	.01	.08	.03	.01	.06	.02	.03	.05	.01	.00	.07
Yellow birch	Poletimber	.05	.05	.05	.13	.09	.01	.07	.06	.09	.03	.12	.09
	Sawtimber	.03	.01	.03	.05	.03	.03	.04	.01	.06	.02	.04	.01
Paper birch	Poletimber	.07	.04	.01	.05	.08	.04	.07	.15	.03	.11	.05	.01
	Sawtimber	.11	.09	.14	.04	.15	.19	.10	.18	.12	.18	.14	.15
Red maple	Poletimber	.44	.28	.17	.18	.17	.34	.43	.14	.20	.44	.15	.22
	Sawtimber	.19	.18	.21	.03	.20	.33	.22	.20	.16	.36	.23	.38
White ash	Poletimber	.00	.02	.04	.05	.01	—	.02	.03	.01	.01	—	.01
	Sawtimber	—	.11	—	.06	—	—	.03	—	.06	.01	—	.04
Hemlock	Poletimber	.41	.27	.41	.16	.30	.24	.28	.21	.02	.40	.24	.03
	Sawtimber	.07	.20	.05	.05	.11	.17	.15	.00	.15	.11	.16	.19
Red spruce and other	Poletimber	.00	.01	.00	.02	—	.00	.01	.00	.00	.07	.00	—
	Sawtimber	—	—	—	—	—	—	—	.02	.01	.02	—	.02

sity class. Some of these differences may be attributable to the range in basal area and size classes.

Annual sawtimber production showed no relation to residual basal area but decreased as the percentage of sawtimber increased (tables 2 and 3). Although Church *(1960)* showed a similar increase and then decrease in average annual sawtimber production, his results were not over a range of residual percentages of sawtimber. Sawtimber production was highest where only 25 to 30 square feet of sawtimber remained in the residual stand, and there was a high percentage of poletimber. Apparently, a high rate of sawtimber growth depends on a high rate of ingrowth into the smaller sawtimber sizes.

Annual poletimber production decreased as residual basal area increased (table 2). However, the change in percentage of sawtimber up to 60 percent did not have a significant influence on poletimber production. The production remains positive up to approximately 80 square feet and then becomes negative. The negative or zero poletimber production in the higher basal areas is not necessarily detrimental; it could mean that the density of smaller trees in the stand is declining slightly or remaining constant.

The basal area growth for the four measurement periods is indicated in figure 1. When the period growth rate is compared with the production increases in table 2, it becomes apparent that 60 square feet of basal area with 45 percent or more sawtimber maintains the best growth response over all the measurement periods. Growth has slowed after 8 years in plots with 80 and 100 square feet of basal area. The high response maintained in plots with 40 square feet is due mainly to the high ingrowth. However, such a stand is understocked for optimum growth *(Solomon and Leak 1969)*.

Accretion

The average annual accretion was approximately the same for the four levels of residual basal area but decreased slightly with increases in percentage of sawtimber (table 2).

Although other work also indicates a small change in accretion as residual basal area increases *(Leak 1961; Blum and Filip 1963; Gilbert et al. 1955)*, the change in accretion in this study is less than the others reported. This is probably due to the differences in the percentage of sawtimber, especially since the sawtimber has a lower annual accretion.

The accretion of poletimber decreased as the percentage of sawtimber increased for all levels of basal area (table 2). The decrease in poletimber growing stock may be the major reason for the decline.

The sawtimber accretion not only increased as the percentage of sawtimber increased; it increased slightly as the basal area per acre increased (table 2). Apparently, sawtimber accretion increases as trees grow from poletimber to sawtimber size.

Ingrowth

As expected, poletimber ingrowth for the stand decreased as the basal area increased (table 2). Although the ingrowth at most of the density levels was almost the same for the three percentages of sawtimber, there was a marked decrease as the percentage of sawtimber increased at the 100-square-foot level. The percentage of sawtimber did not appear to influence the ingrowth unless more than half of the stand was in sawtimber-size trees, although the sapling size distribution is unknown. Ingrowth should decrease as the density of the stand increases.

Leak *(1961)* found that ingrowth in 60-year-old northern hardwoods decreased as residual basal area increased. Other work in slightly older northern hardwoods showed more ingrowth than this study *(Blum and Filip 1963)*. This may be attributed to the more extensive cutting of large trees and the different stand ages.

Over the 10-year period, the basal area growth of trees that grew from poletimber to sawtimber size is shown as sawtimber ingrowth in table 2. Sawtimber ingrowth was less where the percentage of sawtimber in the residual stand was higher at each density level because the sawtimber ingrowth trees were fewer and their growth was slower where the percentage of sawtimber was higher. The sawtimber ingrowth was slightly higher where the residual basal area was higher.

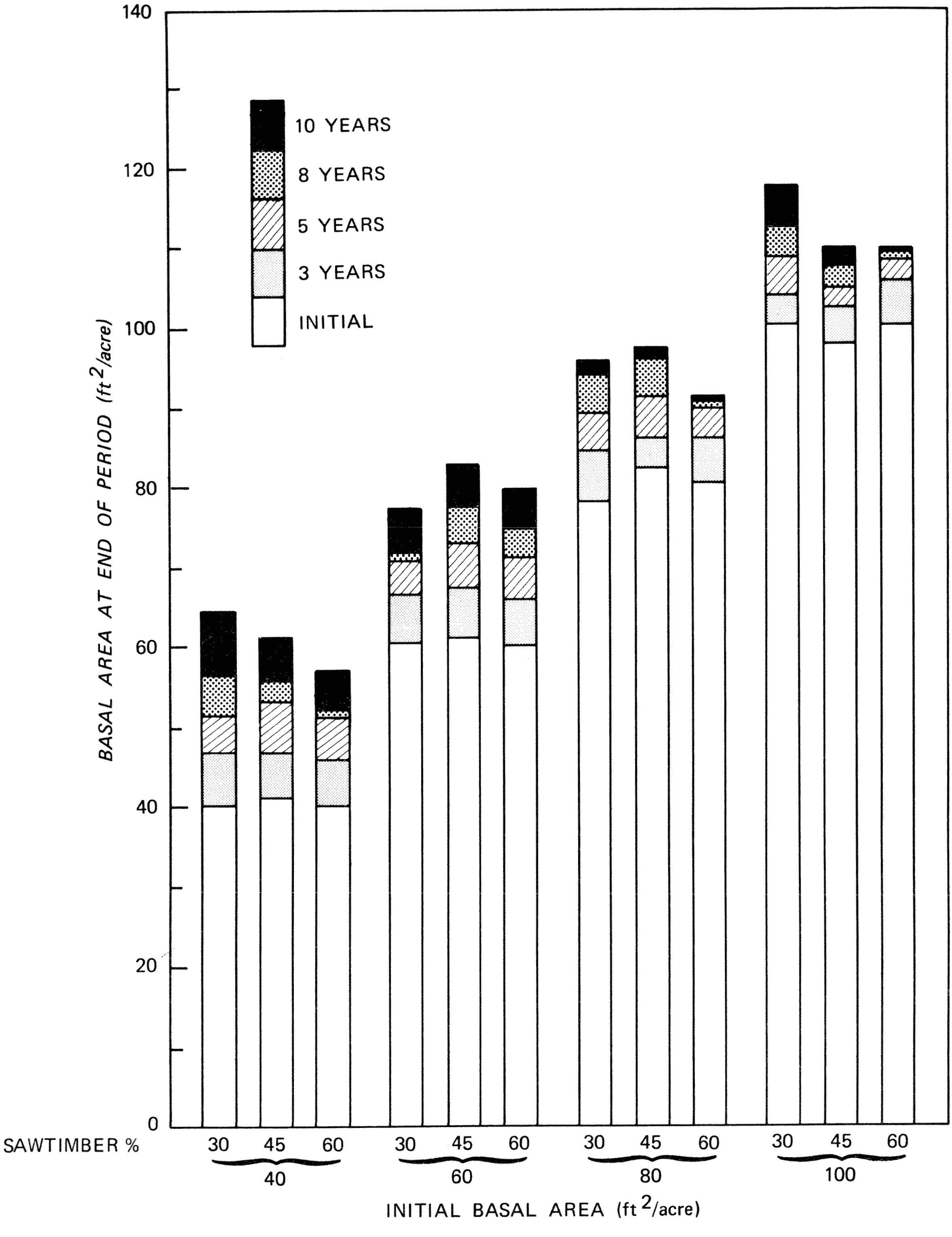
Mortality

The average annual mortality for the entire stand was not clearly related to residual basal area or percentage of sawtimber (tables 2 and 3), although mortality approximately doubled when the residual basal area was increased from 40 to 100 square feet and the percentage of sawtimber increased.

Mortality was similar to that found by Leak *(1961)* but was less than that found by Blum and Filip *(1963)*. The sugar maple stands of the Lake States have lower mortality than the hardwood stands of New England *(Church 1960; Eyre and Longwood 1951; Erdmann and Oberg 1973)*.

Although separate equations were not developed, mortality of poletimber increased as density increased and as percentage of sawtimber decreased. Mortality of sawtimber tends

Figure 1.—Basal area at the ends of consecutive growth periods for the 12 different treatments (poletimber and sawtimber combined).



to be lower when there is a lower percentage of sawtimber in the residual stand. However, the relatively high mortality of sawtimber in the stands with low residual basal areas may be due to the beech scale-nectria complex on beech, since most of it was in beech.

BASAL AREA GROWTH RATES BY SPECIES

The average annual accretion by species showed that hemlock, beech, and red maple responded the most to different levels of residual basal area (table 3). Accretion of all three species decreased as the residual basal area increased and as the percentage of sawtimber increased. Some of this may be due to the decrease in the amount of poletimber in the residual stand.

To compare the basal area accretion of different species, I expressed the annual accretion as a percentage of the initial basal area (table 4). Overall, poletimber outgrew sawtimber up to approximately 80 square feet of basal area. In the higher basal area classes, sawtimber makes better use of the growing space than poletimber. The percentage of annual accretion for sawtimber decreased as the percentage of sawtimber in the stand increased. The higher the stocking level of larger trees, the less the accretion percentage. Poletimber accretion does not follow a set pattern as the percentage of sawtimber in the stand increases.

Beech, hemlock, and red maple had a higher percentage of annual accretion than the totals for all species combined. The percentages for hemlock were the highest of all species, approximately double those of the second highest, beech. The two high percentages at 40 square feet of basal area with 60 percent sawtimber and the high percentage of 80 square feet with 60 percent sawtimber were due to the low initial basal area and high annual growth. Sugar maple, yellow birch, and paper birch were the same with all treatments, with some decrease as basal area increased and percentage of basal area increased.

The mortality of poletimber was highest for beech, and was not closely related to density or to percentage of sawtimber (table 5). However, beech mortality tended to be highest with 40 square feet of basal area. Most of the mortality was in beech because of the beech scale-nectria complex. The mortality for the other species was

Table 4.—Annual accretion, by species, size class, and treatment (in percent of initial basal area)

Species	Size	Treatment 40			60			80			100		
		30	45	60	30	45	60	30	45	60	30	45	60
Beech	Poletimber	7.06	5.79	7.41	3.02	3.83	4.36	2.61	2.68	2.60	3.14	2.26	2.23
	Sawtimber	2.32	2.55	1.80	3.00	2.63	2.67	2.06	2.45	1.83	1.27	1.69	1.74
Sugar maple	Poletimber	—	3.85	3.48	3.44	2.48	1.90	1.10	0.90	1.29	1.01	2.04	1.02
	Sawtimber	—	.00	7.62	4.11	1.59	3.55	3.08	1.21	1.09	2.17	.00	1.13
Yellow birch	Poletimber	2.17	3.65	3.09	2.23	2.15	1.96	1.18	1.34	1.64	1.11	1.19	1.16
	Sawtimber	1.75	.00	2.04	2.87	1.19	1.71	2.86	1.59	1.45	1.41	1.18	.62
Paper birch	Poletimber	1.18	1.62	0.79	1.64	1.67	1.03	1.48	1.84	1.23	1.11	0.82	0.78
	Sawtimber	3.08	1.44	2.21	1.23	2.22	1.42	1.57	1.32	1.57	1.32	1.22	1.11
Red maple	Poletimber	4.43	3.44	5.20	5.40	3.17	2.60	2.20	2.43	2.72	1.44	1.33	1.69
	Sawtimber	6.31	8.26	3.90	5.36	2.65	3.53	2.66	2.82	2.79	2.41	2.06	1.76
White ash	Poletimber	0.00	9.09	10.53	2.20	2.44	—	1.83	4.35	3.85	1.82	—	6.25
	Sawtimber	—	3.85	—	2.68	—	—	6.67	—	1.51	1.45	—	2.38
Hemlock	Poletimber	16.30	14.83	53.25	14.68	12.24	15.48	5.96	8.11	25.00	4.58	4.54	2.00
	Sawtimber	14.00	5.80	3.55	3.18	6.87	4.17	5.60	0.00	3.58	8.27	6.06	3.03
Red spruce & other	Poletimber	0.00	0.00	0.00	3.23	—	0.00	4.76	0.00	—	1.77	0.00	—
	Sawtimber	—	—	—	—	—	—	—	.00	0.00	.00	—	0.00
Total	Poletimber	5.15	4.88	8.11	3.30	3.70	3.42	2.40	2.51	2.26	1.97	1.89	1.65
	Sawtimber	3.89	3.72	2.67	2.78	2.59	2.59	2.65	1.97	1.87	2.10	1.84	1.70

so small that the maples were combined into one category and all others into a third. Sawtimber follows a pattern similar to that of poletimber.

Although most of the mortality that occurred was in beech, the greatest basal area ingrowth was also in beech (table 6). Hemlock was second in the amount of ingrowth, followed by red maple.

Red maple produced the most ingrowth into the sawtimber class (table 7). Beech, yellow birch, and paper birch also had substantial sawtimber ingrowth. Although hemlock did well where it was growing, the larger sizes were not well represented in all treatments. For all species, the 80- and 100-square-foot residual basal area treatments seemed to provide

Table 5.—Annual mortality, by species and treatment (in square feet of basal area per acre and percentage of initial basal area)

Species	Unit	Treatment											
		40			60			80			100		
		30	45	60	30	45	60	30	45	60	30	45	60
		POLETIMBER											
Beech	Ft^2/acre	0.10	0.24	0.16	0.25	0.22	0.15	0.24	0.14	0.12	0.13	0.22	0.22
	percent	1.68	3.76	3.21	1.16	1.76	2.97	1.74	.78	1.12	1.70	1.10	2.14
Maples	Ft^2/acre	0.07	0.06	—	—	0.01	0.05	0.17	0.05	0.10	0.22	0.14	0.13
	percent	.71	.60	—	—	.14	.34	.71	.49	.83	.66	1.19	.73
Others	Ft^2/acre	0.09	0.03	—	0.13	—	—	0.08	0.04	0.03	0.11	0.10	0.13
	percent	.81	.51	—	1.01	—	—	.48	.25	.36	.43	.46	1.39
		SAWTIMBER											
Beech	Ft^2/acre	0.18	0.20	0.55	0.22	—	0.06	—	0.14	0.37	0.08	0.43	0.37
	percent	4.18	5.67	5.22	2.28	—	1.60	—	1.23	2.11	10.00	2.70	3.23
Maples	Ft^2/acre	0.08	0.06	—	—	—	—	—	—	—	—	—	0.10
	percent	2.66	2.75	—	—	—	—	—	—	—	—	—	0.36
Others	Ft^2/acre	—	—	0.05	0.06	—	0.06	—	0.08	0.18	0.17	0.05	—
	percent	—	—	.54	.68	—	.31	—	.54	.84	1.00	.29	—

Table 6.—Average annual ingrowth of poletimber by species and treatment (in square feet of basal area per acre)

Residual basal area	Percent sawtimber	Species							
		Beech	Sugar maple	Yellow birch	Paper birch	Red maple	Hemlock	White Ash Red spruce Other	Total
40	30	.23	—	.02	.02	.30	.25	.01	.83
	45	.37	—	.04	—	.16	.19	.04	.80
	60	.36	.03	.02	—	.08	.29	.02	.80
60	30	.22	.01	.04	—	.02	.19	—	.48
	45	.29	—	.04	.01	.03	.22	—	.59
	60	.26	.03	.01	.01	.07	.18	.01	.57
80	30	.11	.01	—	—	.04	.07	—	.23
	45	.15	.02	—	.02	.02	.10	—	.31
	60	.12	.02	.02	—	.07	.08	.01	.32
100	30	.17	.01	.01	—	.06	.16	.02	.43
	45	.18	.02	.01	—	—	.11	—	.32
	60	.09	—	.01	—	.04	.03	—	.17

Table 7.—Average annual ingrowth of sawtimber by species and treatment (in square feet of basal area per acre)

Residual basal area	Percent sawtimber	Species							
		Beech	Sugar maple	Yellow birch	Paper birch	Red maple	Hemlock	White Ash Red spruce Other	Total
40	30	—	—	.22	.32	.54	.09	—	1.17
	45	.18	.09	.04	—	.45	.14	—	.90
	60	.04	.04	.04	.09	.18	—	—	.40
60	30	.54	.09	.14	.05	.09	.04	.09	1.04
	45	.27	—	.14	.22	.18	.09	—	.90
	60	.09	.04	—	.14	.59	—	—	.86
80	30	.18	.04	.14	.04	.59	.22	.09	1.31
	45	.54	.09	.04	.18	.23	.05	—	1.13
	60	.32	—	—	.09	.18	—	—	.59
100	30	.09	—	.04	.23	.63	.23	.18	1.40
	45	.32	—	.27	.18	.27	.18	—	1.22
	60	.09	.04	—	.14	.23	—	—	.50

favorable conditions for sawtimber ingrowth. Also, as might be expected, the lower percentages of sawtimber in the initial stand for all density levels allowed greater amounts of sawtimber ingrowth.

STRUCTURE

Changes in stand structure for the 10-year growth period are shown in figure 2; the average numbers of trees per acre are plotted over the average diameter for the four plots of each treatment. An increase in ingrowth can be seen in the 5- and 6-inch classes for the 40- and 60-square foot basal area levels; the poletimber sizes also increased over the 10-year period and the size distribution quickly regained a reverse J-shape. At the denser treatment level of 80 square feet, the distribution was maintained in the poletimber class and the number of trees crossing into sawtimber class increased. At the 100-square-foot level there was little or no increase in the poletimber size classes and the sawtimber was maintained. Thus the stand structure at the 80-square foot level remained approximately the same; at the 100-square-foot level there was some decrease in trees, indicated by the mortality increase at the 100-square foot level.

Changes in stand structure occurred mostly in the smaller diameter classes for the lower basal areas and in the larger diameters in the larger basal areas over the 10-year period. The increase in size served to be more uniform for the larger trees than for the poletimber-size trees.

Changes in percentage of sawtimber had no noticeable effect on size distribution.

DIAMETER GROWTH RESULTS

Within density treatments, the average annual diameter growth did not differ among the four remeasurement intervals in the 10-year growth period (table 8). Only the growth of poletimber at the 100-square-foot level declined in average annual rate as the inventory period lengthened. There was a slight decline in the average diameter growth of sawtimber as the period increased, but the annual rates remained similar over most time periods.

Poletimber diameter growth decreased as the level of density increased. The annual diameter growth ranged from 0.06 inches to 0.20 inches. However, there was a decline in the annual rate as the percentage of sawtimber increased at the 80- and 100-square-foot density levels.

The relationship between annual poletimber diameter growth per tree and residual density for the 10-year period may be expressed by:

Poletimber diameter growth $= .2361 - .0018 (x_1)$

here x_1 = residual basal area in square feet.

This equation is significant at the 5 percent level with r = .90 and standard error of mean y = .0029.

Figure 2.—Distribution of diameters at initial inventory and 10 years later, for each of the 12 treatments.

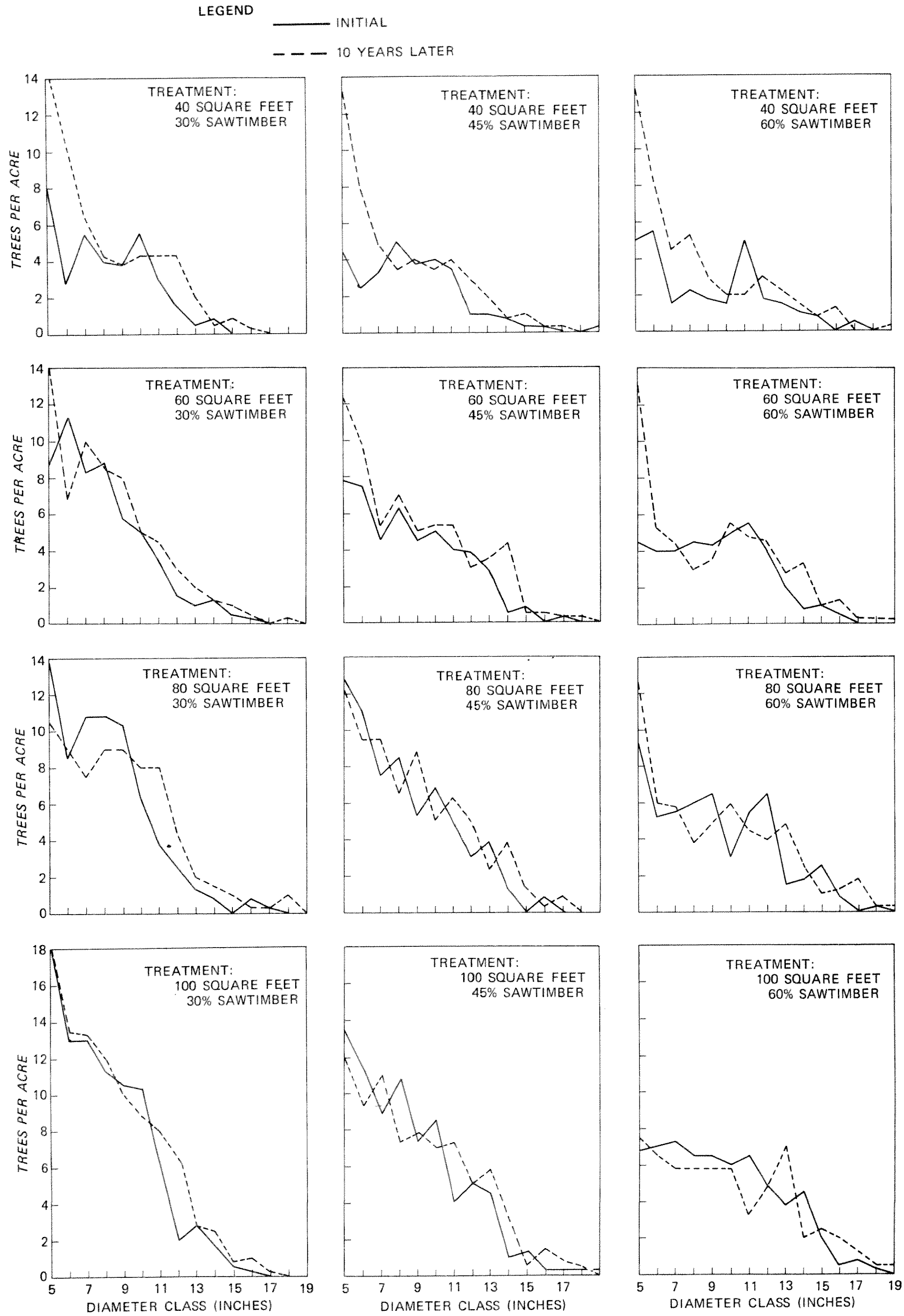


Table 8.—Average annual diameter growth by treatment and size class for different growth periods (in inches)

Residual basal area	Percent sawtimber	Period in years 0–3	0–5	0–8	0–10
		POLETIMBER			
40	30	.16	.17	.16	.17
	45	.15	.17	.16	.16
	60	.19	.20	.19	.20
60	30	.12	.13	.11	.12
	45	.13	.13	.12	.13
	60	.12	.13	.12	.12
80	30	.09	.09	.09	.09
	45	.11	.10	.09	.09
	60	.09	.09	.08	.08
100	30	.08	.08	.07	.07
	45	.09	.08	.07	.08
	60	.08	.07	.06	.06
		SAWTIMBER			
40	30	.16	.16	.15	.15
	45	.15	.15	.16	.17
	60	.17	.16	.15	.15
60	30	.12	.14	.12	.13
	45	.15	.14	.13	.13
	60	.13	.14	.13	.13
80	30	.13	.13	.12	.13
	45	.12	.11	.10	.10
	60	.12	.11	.10	.11
100	30	.10	.12	.10	.10
	45	.11	.10	.09	.10
	60	.10	.10	.10	.10

Annual sawtimber diameter growth per tree ranged from a low of .09 inch to .17 inch for the range in basal area levels. Diameter growth of sawtimber was greater than that of poletimber at the higher density levels. The annual sawtimber diameter growth per tree may be expressed by:

Sawtimber diameter growth = .1881 - .0009 (x_1) where x_1 = residual basal area in square feet.

This equation is significant at the 5 percent level with r = .72 and standard error of mean y = .0029.

The annual diameter growth per tree for the total stand may be expressed by:

Stand diameter growth = .2121 - .0013 (x_1) where x_1 = residual basal area in square feet.

This equation is significant at the 5 percent level with r = .901 and standard error of mean y = .0022.

For comparable residual stand densities, diameter growth rates were slightly higher for both pole and sawtimber stands in the Lake States *(Eyre and Zilligitt 1953; Erdmann and Oberg 1973)*. However, in northern hardwood stands in New England, both pole and sawtimber reached their optimum levels of diameter growth between 60 and 80 square feet of basal area, when diameter growth is still high and site is fully utilized.

SPECIES DIAMETER GROWTH

When separated by species, diameter growth decreased as basal area increased for both pole and sawtimber (table 9). For both size classes, diameter growth either stayed the same or increased slightly as the percentage of sawtimber increased. However, there is tendency for the sawtimber (overstory) to grow slightly faster than the poletimber.

As expected, hemlock of all sizes grew the fastest at all levels of density. But some species, such as paper birch, showed little difference in diameter growth among treatment levels, possibly because the trees present were close to maturity. While beech and red maple made up the largest percentage of the stand, they followed hemlock in growth even though both of them had high mortality. The more tolerant species, such as beech, sugar maple, and yellow birch, showed a more gradual decline in annual diameter growth. Although the growth of the intolerant species, such as paper birch, did not differ much among the different levels of treatment, the growth of intermediate species such as red maple, white ash, and tolerant hemlock decreased with an increase in residual basal area. Except for sugar maple, which had good diameter growth in the low-basal-area classes, hemlock and beech had the fastest growth rates of species considered northern hardwoods in other studies *(Wilson 1953; Gilbert et al. 1955)*. Sugar maple and beech grew as fast in diameter as the Lake States hardwoods *(Eyre and Zilligitt 1953)*.

The diameter growth of trees that later died was highest for beech (table 10). Most of the other species showed minimal growth before death. The relatively good growth of nearly-dead beech may be due to the beech scale-nectria complex, which can cause the tree's bark to swell just before death.

Table 9.—Average annual diameter growth by treatment and species (in inches)

Species	Size class	Treatment 40			Treatment 60			Treatment 80			Treatment 100		
		30	45	60	30	45	60	30	45	60	30	45	60
Beech	Poletimber	0.15	0.14	0.15	0.11	0.12	0.10	0.09	0.10	0.09	0.08	0.08	0.08
	Sawtimber	.15	.12	.13	.13	.14	.13	.11	.11	.11	.08	.11	.11
	All	.15	.14	.15	.11	.12	.11	.09	.10	.09	.08	.08	.08
Sugar maple	Poletimber	—	0.12	0.17	0.13	0.08	0.10	0.04	0.03	0.05	0.03	0.04	0.03
	Sawtimber	—	.36	.26	.12	.05	.19	.13	.05	.06	.06	.02	.07
	All	—	.13	.21	.13	.07	.13	.05	.04	.05	.04	.04	.05
Yellow birch	Poletimber	0.13	0.18	0.12	0.09	0.09	0.07	0.05	0.05	0.06	0.04	0.05	0.04
	Sawtimber	.08	.08	.09	.12	.06	.10	.11	.06	.08	.07	.05	.05
	All	.10	.16	.11	.10	.08	.09	.06	.05	.06	.04	.05	.04
Paper birch	Poletimber	0.07	0.07	0.08	0.07	0.08	0.05	0.06	0.08	0.06	0.05	0.04	0.07
	Sawtimber	.11	.08	.11	.07	.10	.08	.09	.07	.08	.07	.07	.06
	All	.09	.07	.10	.07	.09	.07	.07	.07	.08	.06	.06	.06
Red maple	Poletimber	0.17	0.15	0.18	0.16	0.12	0.11	0.08	0.09	0.10	0.06	0.06	0.07
	Poletimber	.18	.22	.20	.18	.14	.15	.13	.13	.14	.12	.10	.10
	All	.17	.17	.19	.16	.13	.12	.09	.11	.11	.07	.07	.08
White ash	Poletimber	0.03	0.17	0.26	0.10	0.08	—	0.15	0.14	0.15	0.07	—	0.11
	Sawtimber	—	.23	—	.15	—	—	.16	—	.10	.07	—	.17
	All	.03	.21	.26	.12	.08	—	.16	.14	.11	.07	—	.15
Hemlock	Poletimber	0.22	0.30	0.36	0.24	0.24	0.24	0.20	0.18	0.19	0.14	0.15	0.18
	Sawtimber	.32	.31	.22	.21	.28	.19	.23	.19	.21	.20	.22	.19
	All	.23	.30	.35	.24	.24	.23	.20	.18	.20	.14	.16	.19
Red spruce	Poletimber	0.30	—	0.01	0.10	0.21	0.17	—	0.04	—	0.05	0.04	—
	Sawtimber	—	—	—	—	—	—	—	.14	0.05	.08	—	0.17
	All	.30	—	.01	.10	.21	.17	—	.09	.05	.05	.04	.17
Other	Poletimber	—	0.12	0.09	—	—	—	0.16	—	0.07	0.11	—	—
	Sawtimber	—	—	—	—	—	—	—	—	—	.17	—	—
	All	—	.12	.09	—	—	—	.16	—	.07	.12	—	—

Table 10.—Average annual diameter growth of trees that died, by treatment and species (in inches)

Species	Size	Treatment 40			Treatment 60			Treatment 80			Treatment 100		
		30	45	60	30	45	60	30	45	60	30	45	60
Beech	Poletimber	0.16	0.18	0.16	0.08	0.11	0.09	0.09	0.07	0.08	0.08	0.09	0.10
	Sawtimber	.12	.15	.12	.15	—	.11	—	.13	.08	—	.05	.09
	All	.14	.17	.14	.12	.11	.10	.09	.10	.08	.08	.07	.10
Sugar maple	Poletimber	—	0.08	0.20	—	—	0.08	0.01	0.01	0.02	—	0.00	0.01
	Sawtimber	—	—	—	—	—	—	—	—	.04	—	—	—
	All	—	.08	.20	—	—	.08	.01	.01	.03	—	.00	.01
Yellow birch	Poletimber	—	0.06	0.08	0.06	—	—	—	—	0.05	—	0.07	0.08
	Sawtimber	—	—	.08	—	—	—	—	—	—	—	.07	—
	All	—	.06	.08	.06	—	—	—	—	.05	—	.07	.08
Paper birch	Poletimber	0.02	—	—	—	—	—	0.05	0.02	—	—	0.02	—
	Sawtimber	—	—	—	0.12	—	—	—	.01	—	0.03	—	—
	All	.02	—	—	.12	—	—	.05	.02	—	.03	.02	—
Red maple	Poletimber	0.06	—	—	—	0.06	0.02	0.03	—	—	0.02	0.01	0.03
	Sawtimber	.01	0.18	—	—	—	—	—	—	—	—	—	.04
	All	.04	.18	—	—	.06	.02	.03	—	—	.02	.01	.04
White ash, Hemlock, Red spruce, Other	Poletimber	—	—	—	0.00	—	—	—	—	—	0.09	—	—
	Sawtimber	—	—	—	—	—	0.09	—	—	0.00	.08	—	—
	All	—	—	—	.00	—	.09	—	—	.00	.09	—	—

Table 11.—Average annual diameter growth of ingrowth trees by treatment and species (in inches)

Species	Treatment											
	40			60			80			100		
	30	45	60	30	45	60	30	45	60	30	45	60
Beech	0.13	0.11	0.13	0.09	0.12	0.09	0.08	0.15	0.08	0.06	0.08	0.08
Sugar maple	—	—	.13	.12	—	.27	.12	.10	—	—	.20	—
Yellow birch	.16	.25	.16	.15	.12	.50	—	—	.30	—	.00	.06
Paper birch	.08	—	—	—	.22	.03	.00	.01	—	—	—	—
Red maple	.21	.24	.20	.20	.20	.15	.08	.03	.09	.08	—	.19
White ash	—	.19	.26	—	—	—	—	—	—	—	—	—
Hemlock	.28	.31	.37	.27	.28	.25	.20	.20	.23	.11	.19	.15
Red spruce	.30	—	—	—	—	.17	—	—	—	.09	—	—
Other	—	.12	—	—	—	—	—	—	.07	—	—	—

Like the other rates of average diameter growth, the annual growth rate of ingrowth trees decreased as the density increased and remained constant with different percentages of sawtimber (table 11). The species with most rapid growth were hemlock, yellow birch, and red maple, followed by sugar maple and beech. All of the species except hemlock were very close to the overall average shown in table 10. Hemlock ingrowth grew faster than the overall average, indicating the rapid response of hemlock to thinning. It grew approximately twice as much at the lower densities as at the higher densities. Red maple and beech ingrowth followed similar diameter-growth patterns, with a high growth rate at the lower densities that declined rapidly as density increased. The only other species with an ingrowth response to most treatments was yellow birch.

CONCLUSION

In even-aged stands, the main objective is to encourage maximum growth of overstory trees; regeneration, ingrowth, and understory response are of little importance except for their possible influence on the regeneration of the new stand. Notice, in table 2, that maximum sawtimber accretion is obtained by maintaining stocking in sawtimber trees of 60 square feet or more (100 square feet with 60 percent sawtimber). This finding is in line with the recommendations of available stocking guides for northern hardwoods *(Solomon and Leak 1969)*. However, mortality can be high at high sawtimber densities when beech with the beech scale-complex is a significant part of the stand. Therefore it is important to make sure that residual sawtimber trees are vigorous enough to last until the next harvest.

The situation is more complicated in uneven-aged stands. Although high sawtimber accretion is still desirable, we must take care that sawtimber production is maintained by adequate ingrowth into the sawtimber sizes. The treatment that produced the highest sawtimber accretion (100 square feet and 60 percent sawtimber, or 60 square feet of sawtimber) produced quite low sawtimber production (table 2), simply because ingrowth into the sawtimber sizes was not maintained. Furthermore, in the 100-square-foot treatments the poletimber capital is shrinking.

The ideal treatment for an uneven-aged stand to be managed for quality sawtimber is one that maintains high sawtimber production, acceptable sawtimber accretion, and poletimber capital—i.e. it does not reduce the available poletimber. The 60-square-foot density with 45 and 60 percent sawtimber and the 80-square-foot density with 30 or 45 percent sawtimber all produced at least 1.6 square feet of sawtimber production. These treatments produced .7 to .9 square feet of sawtimber accretion, except for the 80-30 treatment which, with only 24 square feet of sawtimber density, produced .64 square feet of accretion (approximately full accretion required 35 to 40 square feet of sawtimber or more). The 60-square-foot treatments (with 45 and 60 percent sawtimber) produced positive poletimber productions, which means that poletimber trees would have to be removed during the next cutting to reestablish the treatment. Since ingrowth slightly exceeds mortality, the 80-square-foot treatments (with 30 and 45 percent sawtimber) produced slightly negative to very slightly positive poletimber production rates, which indicate that a treatment of about 80 square feet with 40 to 45 percent sawtimber would require minimal work in the poletimber sizes to reestablish the treatment.

In summary, a 60-square-foot treatment with about 45 to 60 percent sawtimber seem reasonable for fairly intensive uneven-age management where some cultural or marginal work could be done in the poletimber to improve quality and species composition. A treatment of 80 square feet with about 45 percent sawtimber should be appropriate for less intensive even-age management where little work will be done in the poletimber size. The q-ratio for 45 percent sawtimber is about 1.7 or a little higher while the q for 60 percent sawtimber is about 1.5. These growth data should be useful in making specific predictions of stand response to various levels of density and structure, and they provide some general guidelines for management to achieve optimum basal area growth. Notice that stand growth response will depend upon species composition, since certain species such as hemlock grow much faster in diameter and maintain ingrowth rates better than other species. Since these data were taken from a 70- to 90-year-old stand, caution should be used in applying these results to younger or older stands.

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