USDA FOREST SERVICE
RESEARCH PAPER **NC-199**

10

Stocking and Structure for maximum growth in SUGAR MAPLE selection stands

Thomas R. Crow, Rodney D. Jacobs,
Robert R. Oberg, and Carl H. Tubbs

North Central Forest Experiment Station
Forest Service, U.S. Department of Agriculture

North Central Forest Experiment Station
Forest Service—U.S. Department of Agriculture
1992 Folwell Avenue
St. Paul, Minnesota 55108

Manuscript approved for publication May 2, 1980
1981

STOCKING AND STRUCTURE FOR MAXIMUM GROWTH IN SUGAR MAPLE SELECTION STANDS

Thomas R. Crow, *Supervisory Research Ecologist, North Central Forest Experiment Station, Marquette, Michigan,*

Carl H. Tubbs, *Principal Plant Physiologist, (Currently with Northeastern Forest Experiment Station, Durham, New Hampshire),*

Rodney D. Jacobs, *Cooperative Forest Management Specialist, State and Private Forestry, St. Paul, Minnesota,*

and **Robert R. Oberg,** *Assistant Forestry Technician, North Central Forest Experiment Station, Marquette, Michigan*

Determining optimal stocking, stand structure, and cutting cycle for various management objectives is basic to developing guides for managing forest stands. The existing stocking guide for uneven-aged hardwoods in the Lake States (Eyre and Zillgitt 1953) was based on a synthesis of cutting method studies. This interim guide was thought reliable, but was to be revised and modified as more data became available (Eyre and Zillgitt 1953).

In 1951 a study began at the Upper Peninsula Experimental Forest in northern Michigan to specifically test the effects of stocking level and cutting cycle on growth rates in uneven-aged northern hardwood stands. The stocking levels in this study were 30, 50, 70, and 90 square feet of basal area per acre in trees 9.6 inches d.b.h. and above. Cutting cycles of 5, 10, and 15 years were applied to stocking levels of 50, 70, and 90 square feet. A 20-year cutting cycle was assigned to the 30-foot level. These treatments were applied to mature saw log stands. The 20-year results in terms of basal area and volume growth are reported here. The thousands of measurements made in the 20 years of the study help provide a comprehensive evaluation of existing recommendations for stocking, structure, and cutting cycle in uneven-aged northern hardwood forests. The study results apply best to sugar maple stands on average to better sites (SI_{50} = 55 to 69) in the Lake States.

STUDY AREA

The study was conducted in three hardwood stands dominated by sugar maple (*Acer saccharum* Marsh.). Most stand volume was in saw logs, with relatively little volume in pole-size trees, which is characteristic of mature hardwood stands. Before cutting, the study areas contained from 100 to 152 square feet of basal area per acre (trees 4.6 inches d.b.h. and larger) and averaged 15,000 board feet gross or 11,000 board feet net per acre (Scribner Decimal C). From 1943 to 1946, the entire area was given a light improvement cut. This cut removed an average of 1,300 net board feet per acre. A 1949 salvage cutting removed only dead and windthrown trees, and did not materially change study area stocking.

Sugar maple generally accounted for 70 to 80 percent of the total stand basal area. Other predominant species were yellow birch (Betula *alleghaniensis* Britton), beech (*Fagus grandifolia* Ehrh.), and red maple (*Acer rubrum* L.). Species generally representing less than 1 percent of stand basal area included hemlock (*Tsuga canadensis* (L.) Carr.), basswood (*Tilia americana* L.), elm (*Ulmus americana* L.), red oak (*Quercus rubra* L.), and ironwood (*Ostrya virginiana* (Mill.) K. Koch). Sugar maple reproduction was abundant throughout the study areas.

The study areas were level, and well drained soils predominated. A soil survey lists three common series: Trenary fine sandy loam, Trenary sandy loam, and Munising sandy loam. The Munising series are well to moderately well drained podsols on acidic sandy loam glacial till. The profile is characterized by a friable fine sandy loam in the A horizon, a fragipan at depths of 15 to 30 inches, and a slight to medium acid C horizon (pH 6.0-5.5). It has a better developed fragipan and a more acid C horizon than the similar Trenary series. All three series are considered average or above in site quality. Site index on Munising sandy loam soils on the study sites generally range from 60 to 69[1]. Stand measurements before treatment indicate no significant differences in species composition, stocking, estimated cull, and stand height among the soil series.

STUDY DESIGN AND METHODS

The study consisted of three replications in a completely randomized block design. The first replication was established in the winter of 1951-1952 and the second and third were done during two succeeding winters. Each replication had 10 compartments (10 to 15 acres in size), one for each stocking level-cutting cycle combination. Compartment treatment was randomly assigned. The main effects in the experimental design were cutting cycle (C_i) and residual stocking level (S_j). Assuming no interaction between the replication (R_k) and main effects, the model for any observed value (X) was the sum of an overall mean (μ), treatment effects and their interaction, and a random error:

$$X = \mu + C_i + S_j + R_k + CS_{ij} + E_{e(ijk)}.$$

Cutting cycle was considered a fixed variable. Stocking level, which could not be controlled exactly, was considered a random variable. ANOVA was used to calculate the sum of squares, degrees of freedom, mean square, and F statistic for each factor and the interaction.

Stand measurements were confined to a series of permanent ⅕-acre plots located at fixed intervals along compartment cruise lines. At least 10, and as many as 17 plots were established per compartment. All trees 4.6 inches d.b.h. and larger were mapped, numbered, and listed by species and d.b.h. After each plot's basal area was computed, enough trees were marked for cutting to reduce the plot's residual basal area of trees 9.6 inches d.b.h. and larger to prescribed levels. Most ⅕-acre plots were marked to within ±2 square feet of the desired residual area. The remainder of the stand within a compartment was marked to the desired stocking level by ocular estimates. In marking, poor quality and high risk trees were generally selected for removal, leaving the most promising trees for growing stock. After the first 5-year cycle, each compartment was partitioned into 0.8- to 1.0-acre blocks, 100 percent tallied, and marked to ±3 feet of the prescribed stocking for trees 9.6 inches d.b.h. and over. The methodology change avoided the difficulties of controlling stocking on small plots, but growth data collection continued on the same ⅕-acre plots. Compartments were marked using Arbogast's guide (1957).

Measurements were made at 5-year intervals following the establishment of each replication. The 5-year cycle cuts for the first replication were in 1951, 1956, 1961, and 1966. The 10- and 15-year cycle cuts were done in 1951 and 1962, and 1951 and 1966, respectively. The 20-year cycle cut (30 square-foot level only) was made in 1951. Cuts in replications two and three were 1 and 2 years later, respectively. The cutting history of each replication and treatment is presented in table 1.

Following the initial cutting, all ⅕-acre plots were checked to make corrections for trees lost during logging and to detect any trees marked but not cut. Data on total height, merchantable saw log height, height to the lowest living branch, cull class, tree quality and form were also taken on five or more sample trees per plot as part of the post-logging measurements.

A wind storm occurred on June 30, 1953, after replications one and two were established and cut but before replication three was installed. Severe damage was limited to a narrow strip across the Experimental Forest. Flanking this strip, scattered patches of breakage and windthrow occurred. Parts of replications one and two were within the strip of maximum destruction and three compartments—30/20 rep 2, 50/5 rep 1, and 50/15 rep 2—were replaced at the same time and in the same general area as replication 3.

Both volume and basal area growth were analyzed for the four study measurement periods. Fifth-acre measurements were summed to a per acre basis and growth was computed annually for each period. The recognized units of growth included survivor growth, ingrowth, and gross and net growth. Mortality was also recorded. The study used definitions presented by Erdmann and Oberg (1973):

[1]*Personal communication with G. Erdmann.*

Table 1.—*Summary of original stocking and cutting history by treatments for trees 4.6 inches d.b.h. and larger and for trees 9.6 inches d.b.h. and larger*

(level) Stocking (~~percent~~)	Cutting cycle (years)	Original stand			Initial cut			Second cut			Third cut			Fourth cut		
		Replications														
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
BA (sq ft/acre)—TREES ≥ 4.6 INCHES D.B.H.																
30	20	130.1	125.8	138.2	92.7	87.6	100.7									
50	5	109.3	147.9	100.8	46.1	90.8	41.9	8.3	6.1	5.8	9.8	6.9	8.5	8.5	7.0	13.8
	10	152.5	127.5	124.9	96.7	69.1	68.9				10.4	19.5	18.1			
	15	110.1	110.9	132.4	51.5	46.7	73.1							19.6	20.5	22.4
70	5	146.6	123.5	122.6	70.4	44.5	45.3	8.6	0.0	7.8	6.5	16.9	7.9	12.5	11.1	12.6
	10	124.7	132.8	129.7	48.2	51.9	53.1				6.5	12.2	19.3			
	15	142.2	146.2	121.1	60.5	69.4	43.3							19.2	18.8	20.3
90	5	143.5	141.5	142.4	51.8	44.7	44.9	3.7	5.5	6.3	3.4	11.1	12.8	8.0	7.1	5.6
	10	130.8	127.7	120.6	31.8	32.1	25.1				10.0	16.1	5.9			
	15	139.9	138.4	127.8	46.1	40.3	30.3							12.6	10.3	8.4
BA (sq ft/acre)—TREES ≥ 9.6 INCHES D.B.H.																
30	20	118.9	114.4	125.6	89.1	84.2	96.6									
50	5	93.3	135.6	88.9	43.6	86.0	39.6	7.6	5.9	5.8	9.5	6.9	7.9	8.4	6.9	13.5
	10	143.9	116.0	113.4	93.7	64.6	66.0				6.7	19.1	17.2			
	15	98.5	89.0	118.8	49.1	42.0	68.4							12.9	20.5	22.1
70	5	136.3	111.3	109.4	67.5	42.2	42.5	8.5	0.0	7.4	6.4	16.6	7.4	3.5	10.8	12.6
	10	113.5	117.6	118.5	45.5	35.1	49.4				6.4	11.9	19.0			
	15	131.5	136.2	109.1	59.3	66.7	40.3							18.5	18.8	20.3
90	5	133.9	129.6	129.4	49.4	41.8	40.4	3.6	5.5	5.8	3.4	11.0	12.7	7.4	7.0	5.5
	10	119.8	117.8	108.1	30.4	24.8	22.1				9.8	14.6	6.0			
	15	130.3	126.2	118.2	43.0	37.8	27.6							12.2	19.6	4.7
VOLUME (cu ft/acre)—TREES ≥ 4.6 INCHES D.B.H.																
30	20	4245.0	4038.0	4491.8	3066.2	2833.6	3310.8									
50	5	3516.1	4830.0	3271.4	1513.4	2987.6	1380.9	263.8	203.0	191.1	323.5	230.6	279.5	280.9	226.6	458.2
	10	5005.7	4160.7	4065.9	3197.0	2275.2	2269.8				343.6	538.5	596.2			
	15	3591.4	3545.7	4296.3	1701.5	1523.1	2394.4							646.3	679.4	742.3
70	5	4793.6	4013.5	3982.3	2322.2	1466.8	1482.3	284.0	0.0	256.6	216.6	560.1	259.6	409.9	369.7	420.2
	10	4067.5	4292.1	4229.2	1586.4	1697.4	1736.1				215.1	400.8	635.9			
	15	4639.9	4764.7	3940.3	1996.3	2264.4	1417.7							636.7	624.6	677.8
90	5	4691.0	4602.3	4626.4	1708.3	1445.6	1457.9	122.5	181.8	205.6	112.1	368.3	423.0	261.4	238.2	185.7
	10	4266.7	4162.0	3921.3	1045.7	1050.1	1811.8				327.8	532.6	198.1			
	15	4577.7	4520.2	4173.3	1510.9	1322.6	985.3							417.1	679.2	277.8
VOLUME (cu ft/acre)—TREES ≥ 9.6 INCHES D.B.H.																
30	20	3930.0	3720.4	4135.2	2965.1	2742.5	3198.8									
50	5	3067.4	4483.8	2937.9	1442.5	2853.8	1317.0	243.8	197.3	0.0	314.2	229.1	240.8	278.2	202.6	450.2
	10	4765.0	3839.1	3739.9	3114.2	2172.4	2188.8				339.5	529.3	570.6			
	15	3257.1	2927.7	3914.1	1635.2	1399.4	2266.1							627.9	679.4	731.1
70	5	4504.9	3671.0	3613.4	2242.0	2258.9	1405.3	282.3	0.0	244.9	210.6	551.9	248.0	401.0	362.0	420.2
	10	3751.6	3865.0	3914.7	1508.9	1604.2	1634.4				214.2	393.5	628.2			
	15	4338.5	4481.9	3600.3	1961.4	2206.2	1335.2							617.2	606.3	677.8
90	5	4421.3	4268.0	4259.9	1642.4	1363.7	1334.7	117.8	181.8	201.4	112.1	366.4	417.6	244.3	234.6	180.5
	10	3954.4	3885.4	3570.2	1007.4	986.6	1728.2				323.8	522.9	198.1			
	15	4304.9	4176.5	3904.3	1425.3	1250.9	910.4							406.9	651.7	274.1

Survivor growth—Growth on trees present at both the beginning and end of a measurement period within a given size class.

Ingrowth—Growth on trees that grew into the 4.6-inch d.b.h. class during a measurement period (new growing stock) or growth on trees that grew into the 9.6-inch d.b.h. class (new saw log tree).

Mortality—Volume or basal area of all trees that died during a measurement period.

Cubic foot volumes were obtained from composite volume tables for the Lake States (Gevorkiantz and Olsen 1955). Board foot volumes (Scribner rule) were obtained from local volume tables prepared for the Upper Peninsula Experimental Forest. Gross growth was calculated for each measurement period by adding survivor growth and ingrowth. Gross growth minus mortality equalled net growth.

Both residual stocking and structure affect growth, but it is often difficult to separate them in analyzing field experiments. To better test this interaction, Moser's (1974) growth model for northern hardwoods was applied to a variety of stocking levels and structures. The cutting studies reported by Eyre and Zillgitt (1953) provided the basic data for developing Moser's projection system. Tests using our study's 1951 data as initial conditions and projecting 1971 measurements show the model is a valuable predictive tool (Moser *et al.* 1979). The model provides estimates of basal area, volume, and number of trees by size classes for ingrowth, survivor growth, and mortality.

Stand structure can be characterized by size-class distribution, which in an ideal all-age forest, follows a simple geometric progression. The ratio between the number of trees in succeeding size classes is called q. The number of trees in a size class multiplied by q equals the number in the next smaller size class. A low q (1.1) describes a stand with proportionally more large trees, while a large q (1.5) describes a stand with proportionally more small trees. A q of 1.3 is generally recommended for northern hardwoods in the Lake States (Tubbs and Oberg 1978). A range of q values from 1.1 to 1.4 were tested in the model, each applied to the stocking levels (30, 50, 70, and 90) considered. A diameter distribution was calculated by 2-inch diameter classes (assuming a maximum diameter of 24 inches d.b.h.) for each q factor and stocking level combination. These data representing a variety of stand structures and stockings were used as initial conditions in a 20-year simulation.

RESULTS AND DISCUSSION

Basal Area Growth

Length of cutting cycle affected growth rates, although differences were small and statistically nonsignificant. Survivor growth increased and mortality decreased with decreasing cutting cycle, resulting in net annual basal area growth averaging 2.05, 1.96, and 1.89 square feet per acre for the 5-, 10-, and 15-year cycles, respectively (table 2). Mortality differences among cutting cycles were more evident at the lower stockings (50 and 70 square feet), while survivor growth differences were more evident at the higher stocking (90 square feet). More frequent entry into the stand reduced competition and allowed removal of high risk trees. No differences were evident for ingrowth by cutting cycle. In all cases, the variation within each cutting cycle was substantial, and differences in net growth among cycles did not differ at the 95 percent level of probability.

The lack of significant responses by cutting cycles allowed the pooling of data for considering the impact of residual stocking level on growth (table 3). The 30 square foot stocking level/20-year cutting cycle was also added to the comparisons in table 3. Results indicate average annual net basal area growth remained relatively constant over the range of residual basal areas. At 30, 50, and 70 square feet of residual basal area, net growth for trees 4.6 inches d.b.h. and larger was similar, averaging 2.08 to 2.09 square feet/acre/year, and was slightly less, 1.73 square feet/acre/year, at 90 square feet of basal area. For sawtimber-size trees, net growth ranged from 1.50 to 1.77 square feet/acre/year across the range of stocking levels. A uniform response showed in the study's 5-year results (Church 1960), and net growth uniformity across a wide range of stocking levels has been reported for second-growth hardwoods in the Lake States (Erdmann and Oberg 1973), the Northeast (Solomon 1977), and the Appalachians (Trimble 1968).

The net growth range for the mature stands treated in this study was below the 2.32 to 3.22 square feet of annual basal area growth (trees 4.6 inches d.b.h. and larger) recorded for six cutting treatments made in northeastern Wisconsin over 15 years in second-growth stands dominated by sugar maple, basswood, yellow birch, and white ash (Erdmann and Oberg 1973). Comparative values are expected to converge after several mature stand cuts decrease the proportions of large over-mature trees and increase the representation of fast growing poletimber and small saw logs. In fact, net growth values during the last measurement period at 50 and 70 square feet of residual basal area were within the range of values cited by Erdmann and Oberg (1973) for second growth forests.

Based on a composite of studies, Jacobs (1968) cited an average gross basal area of 2.5 square feet/acre/year (in trees 4.6 inches d.b.h. and larger) for selection stands on the Upper Peninsula Experimental Forest. This is very close to the gross production rate recorded for this study's last measurement period at 30, 50, and 70 feet of residual stocking. Jacobs (1968) further stated that "with continued management, as the small trees develop and the overstory vigor improves, basal area growth may reach 3 square feet/acre/year." The maximum gross rate recorded for any combination of treatments and measurement period in our study was 2.99 square feet/acre/year (N = 108). Thus, 3 square feet would seem a valid upper bound for the stand and site conditions studied here, but average figures are substantially lower.

Although differences in average annual survivor growth were not significant ($P > 0.05$) among stocking levels, maximum survivor growth occurred at 70 square feet of stocking for all cutting cycles and the minimum occurred in all cases at 90 square feet (table 2). At 70 square feet, survivor growth ranged from 1.32 to 2.34 square feet/acre/year among replications, cutting cycles, and measurement periods (N = 36), compared to a range of 1.19 to 2.01 at 90 square feet of residual stocking. In comparison to the maximum at 70, the reduced levels of survivor growth at 90 square feet can be explained by increased competition, advanced age, and less opportunity to rid stands of poor growers. At 30 and 50 square feet, stands were initially understocked for survivor growth. By the last growth period, however, survivor growth at these stocking levels exceeded or equalled that measured at 70 square feet (fig. 1).

Table 2.—*Average annual basal area growth in square feet per acre (trees 4.6 inches d.b.h. and larger) and standard deviations by growth component, stocking level, and cutting cycle (Mean values are based on three replications and four measurement periods, N = 12)*

Cutting cycle (years)	Residual stand density (sq ft/acre) 50	70	90	$\bar{x}$ (SD)
SURVIVOR GROWTH				
5	1.82	1.95	1.78	1.85(0.34)
10	1.83	1.89	1.75	1.82(0.28)
15	1.82	1.91	1.70	1.81(0.23)
$\bar{x}$ (SD)	1.82(0.33)	1.92(0.27)	1.74(0.22)	
INGROWTH				
5	0.43	0.43	0.25	0.37(0.15)
10	0.45	0.37	0.27	0.37(0.13)
15	0.40	0.34	0.27	0.35(0.13)
$\bar{x}$ (SD)	0.43(0.15)	0.38(0.11)	0.27(0.10)	
GROSS GROWTH				
5	2.25	2.38	2.03	2.22(0.42)
10	2.28	2.28	2.02	2.19(0.35)
15	2.22	2.25	1.97	2.15(0.31)
$\bar{x}$ (SD)	2.25(0.40)	2.30(0.33)	2.01(0.27)	
MORTALITY				
5	0.10	0.15	0.25	0.17(0.18)
10	0.19	0.22	0.26	0.23(0.22)
15	0.20	0.28	0.31	0.26(0.33)
$\bar{x}$ (SD)	0.16(0.22)	0.22(0.31)	0.28(0.23)	
NET GROWTH				
5	2.15	2.23	1.78	2.05(0.52)
10	2.09	2.04	1.76	1.96(0.49)
15	2.02	1.97	1.66	1.89(0.52)
$\bar{x}$ (SD)	2.09(0.54)	2.08(0.54)	1.73(0.35)	

Table 3.—*Average annual gross and net basal area growth, survivor growth, ingrowth, and mortality for trees 4.6 inches d.b.h. and larger and for trees 9.6 inches and larger*

(In square feet of basal area/acre/year)

Stocking level[1]	Survivor growth	Ingrowth[2]	Gross growth	Mortality	Net growth
TREES 4.6 INCHES D.B.H. AND LARGER					
30	1.77	0.56	2.33	0.25	2.08
50	1.82	0.43	2.25	0.16	2.09
70	1.92	0.38	2.30	0.22	2.08
90	1.74	0.27	2.01	0.28	1.73
TREES 9.6 INCHES D.B.H. AND LARGER					
30	1.02	0.66	1.68	0.18	1.50
50	1.16	0.71	1.87	0.14	1.73
70	1.37	0.55	1.92	0.14	1.78
90	1.34	0.42	1.76	0.26	1.50

[1]Unit: residual basal area, square feet/acre. Figures for 50, 70, and 90 square feet represent averages for three cutting cycles, 5, 10, and 15 years. At 30 square feet the cutting cycle was 20 years.

[2]Ingrowth represents sapling ingrowth into poletimber for 4.6 inches d.b.h. and larger, and poletimber ingrowth into sawtimber for 9.6 inches d.b.h. and larger.

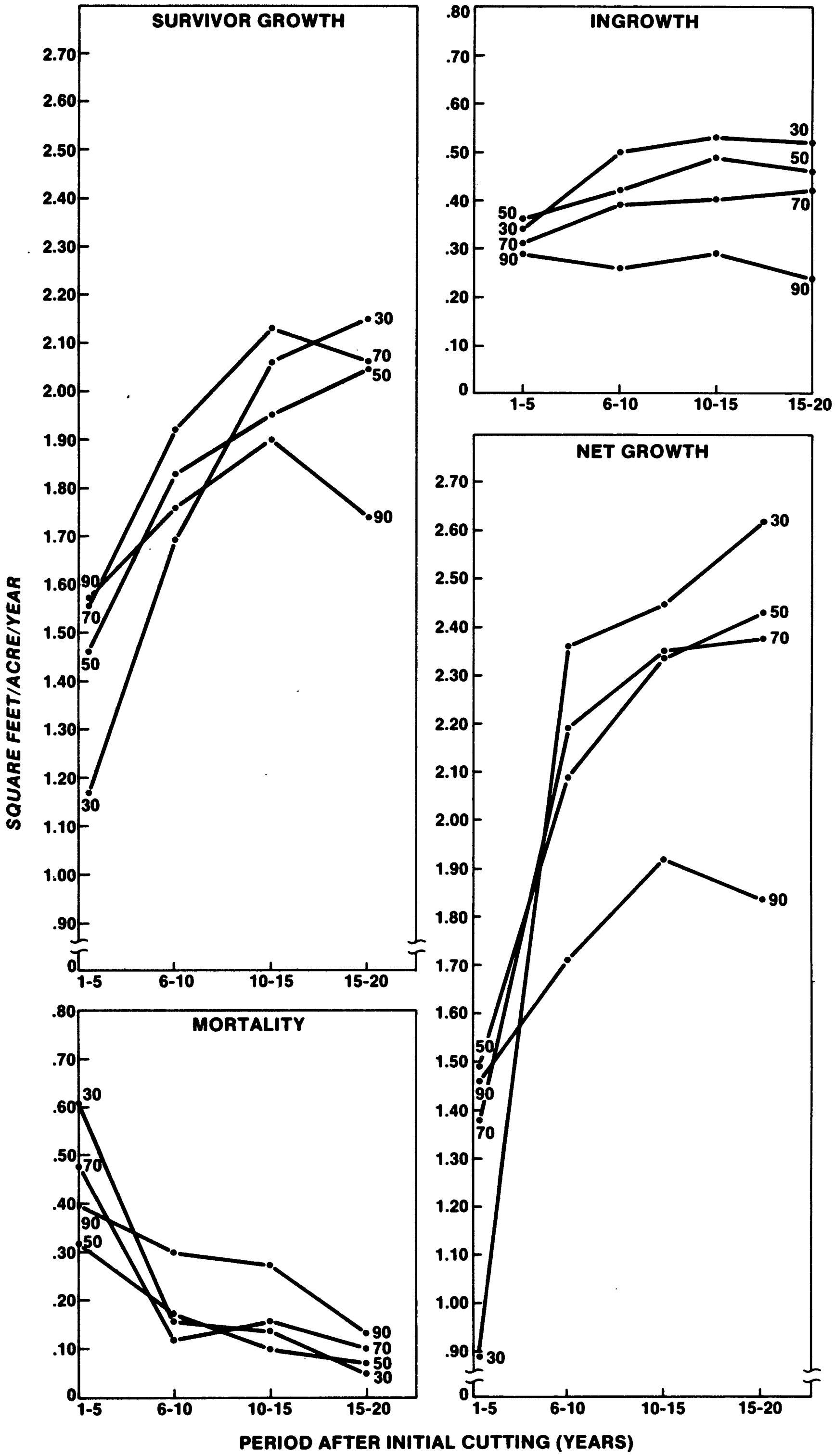

Figure 1.—*Average survivor growth, ingrowth, mortality, and net growth (trees ≥ 4.6 inches d.b.h.) expressed as basal area (square feet/acre/year) by measurement period. Averages based on N = 9 (three cutting cycles, three replications) for 50, 70, and 90 square feet; N = 3 (one cutting cycle, three replications) for 30 square feet.*

Ingrowth accounted for a declining proportion of net annual growth with increasing stocking. At 30 square feet, ingrowth represented 27 percent of net growth, compared to 16 percent at 90 square feet (table 3). Similar trends were noted for ingrowth into the sawtimber class. At 30 square feet, ingrowth into the saw log class was 44 percent of net growth. It declined to 28 percent at 90 square feet. The maximum value recorded for any measurement period, stocking level, cutting cycle combination was 1.23 square feet of ingrowth per acre per year at 30 square feet of stocking and 20-year cutting cycle.

Reduced mortality results from converting slow-growing unmanaged stands to thrifty, managed stands. In an unmanaged stand similar to those in this study, annual mortality averaged 1.23 square feet/acre and almost equalled growth (Eyre and Zillgitt 1953). In managed stands, partial cutting reduced this figure by more than two-thirds. Average study mortality rates increased at the lowest and highest stocking levels and were lowest in intermediate levels (table 3). Higher mortality at 90 square feet occurred when light cutting did not remove a majority of high-risk trees. Other differences are probably not closely related to stocking level. Additional mortality factors are discussed later.

Substantial changes did occur for most growth parameters during the four measurement periods (fig. 1). After a large second period net growth increase, smaller increments were recorded for several growth periods. Maximum gross and net growth rates occurred 10 to 15 years after the initial treatment, and steady increases continued for many individual plots throughout the 20 years of measurement. During the last growth period, net annual growth was inversely related to basal area stocking, with rates at 90 square feet significantly lower ($P < 0.01$) than those at 30, 50, and 70 square feet. The mean net growth recorded for 30, 50, and 70 square feet during the fourth growth period, 2.40 to 2.60 square feet/acre/year, probably best represents the average net annual growth than can be expected for these stands and sites under managed conditions.

Growth components changing the most were survivor growth and mortality. Survivor growth increased from an annual average (all stocking levels) of 1.53 square feet/acre during the first 5 years to 1.84 during the next 5 years, and reached a maximum value of 1.99 after 15 years. Slight declines occurred at 70 and 90 square feet during the last period. By the end of the study, survivor growth varied inversely with stocking level (fig. 1).

Maximum mortality rates were recorded during the first measurement period and declined thereafter (fig. 1). High mortality is not unusual following the first cut in unmanaged stands. During the study's first 5-year period, average annual mortality ranged from 0.32 to 0.62 square foot/acre. After the first period, however, mortality was essentially the same for 30, 50, and 70 square feet, and in the last period, mortality was relatively unimportant regardless of stocking (fig. 1).

Mortality figures for the first measurement period were greatly influenced by the 1953 windstorm and logging damage following the heavy initial cut in the treatment stands. Plot surveys following the initial cut and the 1953 storm identified mortality due solely to those factors. Summaries by stem number and basal area indicate over half of the total mortality and in some treatments as much as 90 percent during the first period was due to logging damage and windthrow (table 4). Data also indicate storm-associated mortality was not density dependent but was related to storm path proximity.

Ingrowth varied only slightly by measurement period (fig. 1). Although ingrowth rates were somewhat lower during the first period at 30, 50, and 70 square feet, they were not significantly different ($P > 0.05$) from subsequent rates. Little or no change occurred with time at 90 square feet.

These data showed the need for long-term measurements. Because rapid changes occurred in mortality and survivor growth during the study's first 10 years, erroneous conclusions and recommendations could easily result if based solely on early information. Nor do 20-year averages necessarily represent differences in stand response among treatments. Greater weight should be given those data from the last two measurement periods.

Cubic-foot Volume Growth

The trends for cubic foot volume (table 5) are similar to those for basal area growth. Twenty-year averages for net and gross cubic foot growth varied little by stocking level and cutting cycle. Average rates at 30, 50, and 70 square feet were almost identical and rates at 90 square feet were only slightly less.

Again, considering only 20-year averages can be misleading due to changes in volume increment with time. Variation by measurement period in mean annual volume growth (net) for trees 4.6 inches d.b.h. and larger can be seen in table 6. At the study's end, stocking level and net annual growth showed a clear relation.

Table 4.—*Factors responsible for poletimber and saw log mortality during the first measurement period (values are based on totals for three replications in each treatment)*

Factor	Number of trees	Percent of total	Basal area (sq. ft.)	Percent of total
		30/20[1]		
Windstorm	23	38	13.47	56
Logging damage	28	47	5.28	22
Other	9	15	5.36	22
		50/5		
Windstorm	20	47	8.15	55
Logging damage	18	43	5.78	39
Other	4	10	0.89	6
		50/10		
Windstorm	8	25	10.30	46
Logging damage	13	39	4.31	19
Other	12	36	7.92	35
		50/15		
Windstorm	9	23	8.14	34
Logging damage	20	50	10.06	42
Other	11	27	5.75	24
		70/5		
Windstorm	2	7	2.18	13
Logging damage	17	61	5.87	35
Other	9	32	8.72	52
		70/10		
Windstorm	15	47	18.92	79
Logging damage	10	31	3.59	15
Other	7	22	1.44	6
		70/15		
Windstorm	17	46	20.48	70
Logging damage	5	14	1.76	6
Other	15	40	7.02	24
		90/5		
Windstorm	9	26	12.52	47
Logging damage	17	50	5.33	20
Other	8	24	8.79	33
		90/10		
Windstorm	4	21	6.66	33
Logging damage	8	42	3.23	16
Other	7	37	10.29	51
		90/15		
Windstorm	13	36	14.67	55
Logging damage	13	36	3.40	13
Other	10	28	8.64	32

[1]Residual stocking (basal area in trees ≥ 9.6 inches d.b.h.)/cutting cycle.

Table 5.—*Average annual gross and net volume growth, survivor growth, ingrowth, and mortality for trees 4.6 inches d.b.h. and larger and for trees 9.6 inches d.b.h. and larger*

(In cubic feet/acre/year)

Stocking level[1]	Survivor growth	Ingrowth[2]	Gross growth	Mortality	Net growth
TREES 4.6 INCHES D.B.H. AND LARGER					
30	59.08	14.43	73.51	7.74	65.77
50	60.93	11.16	72.09	5.25	66.84
70	64.14	9.80	73.94	6.95	66.99
90	58.20	6.94	65.14	9.02	56.12
TREES 9.6 INCHES D.B.H. AND LARGER					
30	35.29	20.40	55.69	5.84	49.85
50	39.59	20.60	60.19	4.43	55.76
70	46.63	16.76	63.39	5.83	57.56
90	45.44	11.78	57.22	7.79	49.43

[1]Unit: residual basal area, square feet/acre. Figures for 50, 70, and 90 square feet represent averages for three cutting cycles, 5, 10, and 15 years. At 30 square feet the cutting cycle was 20 years.

[2]Ingrowth represents sapling ingrowth into poletimber for 4.6 inches d.b.h. and larger, and poletimber ingrowth into sawtimber for 9.6 inches d.b.h. and larger.

Table 6.—*Average annual net growth in cubic feet per acre and standard deviation for trees 4.6 inches d.b.h. and larger by stocking level and measurement period (Averages are based on N = 3 for 30 square feet and N = 9 for 50, 70, and 90 square feet.)*

Stocking Level (ft^2e/acre)	Measurement Period 1	2	3	4
	$\bar{x}$ (SD)—ft^3/acre/yr			
30	28.48(30.25)	73.17(4.86)	77.59(4.72)	83.84(3.57)
50	47.78(15.82)	66.87(14.80)	74.77(11.39)	77.91(10.22)
70	44.72(16.07)	70.80(8.20)	75.81(9.06)	76.59(11.05)
90	47.90(9.49)	55.43(14.02)	62.17(9.32)	59.79(4.27)

During the first measurement period, net annual cubic-foot volume growth varied from –6.15 to 70.52 among the various treatments and replications (N = 30). This compares to a range of 53.01 to 94.75 cubic feet/acre/year for the last period. Figures available for second-growth sugar maple stands are substantially higher. For example, Erdmann and Oberg (1973) reported a range from 102 to 123 cubic feet/acre/year (averages) for a cutting methods study in a sugar maple-dominated second growth forest.

Board-foot Volume Growth

The trends for board foot growth paralleled those of other units, except an optimum stocking is more obvious when dealing strictly with saw logs (table 7). The maximum net growth at 70 square feet confirmed the optimum stocking recommended by Eyre and Zillgitt (1953) based on their analysis of several cutting methods. The advantage at 70 square feet continued throughout the study (fig. 2). Most of the explainable differences in net board foot growth among treatments were due to survivor growth. At 30 and 50 square feet of residual stocking, stands were clearly understocked for sawtimber growth (fig. 2).

Ingrowth into saw log classes did not differ greatly because the initial stands were understocked with poletimber (fig. 2). Sapling numbers were greatly affected by the treatments (Tubbs 1968), but sapling growth rates were not large enough to affect saw log ingrowth. As management proceeds, ingrowth should vary substantially by treatment.

In mature stands, advanced age increases mortality risk during the initial management period, and at 90 square feet fewer opportunities to remove trees before they died and became unmerchantable resulted in higher mortality rates (table 7). With continued management, factors such as increasing tree vigor and declining average age minimized mortality differences among stocking levels (fig. 2).

Wide variation in net board foot growth among similarly treated replications was evident (table 8). The correlation coefficient relating stocking and net growth was $r = 0.48$, indicating that factors other than total stocking were important in determining board foot growth. Other possible factors are site quality, tree age and vigor, stand structure variations, species, and cutting cycle.

Table 7.—*Average annual growth in board feet per acre (Scribner rule) for trees 9.6 inches d.b.h. and larger*

Residual basal area	Survivor growth	Ingrowth	Gross growth	Mortality	Net growth
30	179	18	197	20	177
50	201	18	219	15	204
70	243	14	257	22	235
90	235	10	245	32	213

To further explore how stocking affects board foot growth, the best and worst gross growth for each replication during the 20 years (excluding the 30 square foot treatment) were plotted and fit with a polynominal curve (fig. 3). Average growth declined sharply in stands with stocking less than 60 square feet and more than 90 square feet. However, very good growth (300 board feet/acre) can occur between about 50 square feet and 90 square feet. The best possibility for optimum growth is at 60 to 80 square feet of residual basal area in trees over 10 inches d.b.h. (fig. 3). Stands growing at about 2.0 square feet of basal area net growth, with residual basal areas between 60 and 70 square feet, and cut at intervals between 5 and 15 years, should remain within the stocking level range producing maximum growth.

According to Eyre and Zillgitt (1953), a net average annual growth of 200 board feet/acre should be obtainable for managed northern hardwood stands on good Lake State upland sites. After the first measurement period, average net growth exceeded 200 board feet/acre/year for all treatments except the lowest stocking level (table 8). Growth rates after the first period at 70 square feet averaged 260 and 270 board feet (net) /acre/year and 300 to 320 board feet/acre/year were recorded for several growth periods in replications at 50, 70, and 90 square feet of residual stocking.

D.b.h. Growth

Results indicate partial cutting can sharply increase average stand diameter growth. Average 20-year diameter growth for sugar maple in unmanaged stands is usually approximately 2.0 inches (Jacobs 1968). Average study 20-year growth ranged from 4.28 inches for a 6-inch (beginning d.b.h.) tree at 50 square feet to 2.35 for a 6-inch tree at 90 square feet (table 9).

Average diameter growth of sugar maple generally declined from the smallest to largest trees, from the lightest residual stocking to the heaviest, and from the shortest to the longest cutting cyle. Yellow birch, the only associated species numerous enough to analyze, with a beginning diameter of 6 inches outgrew sugar maple with a similar beginning diameter, but larger yellow birch grew more slowly than sugar maple.

Maximum sugar maple growth rates were summarized to indicate diameter growth potential (table 9). Growth rates as high as 7 and 8 inches were recorded on 6-inch class trees for the 20-year period. Twelve-

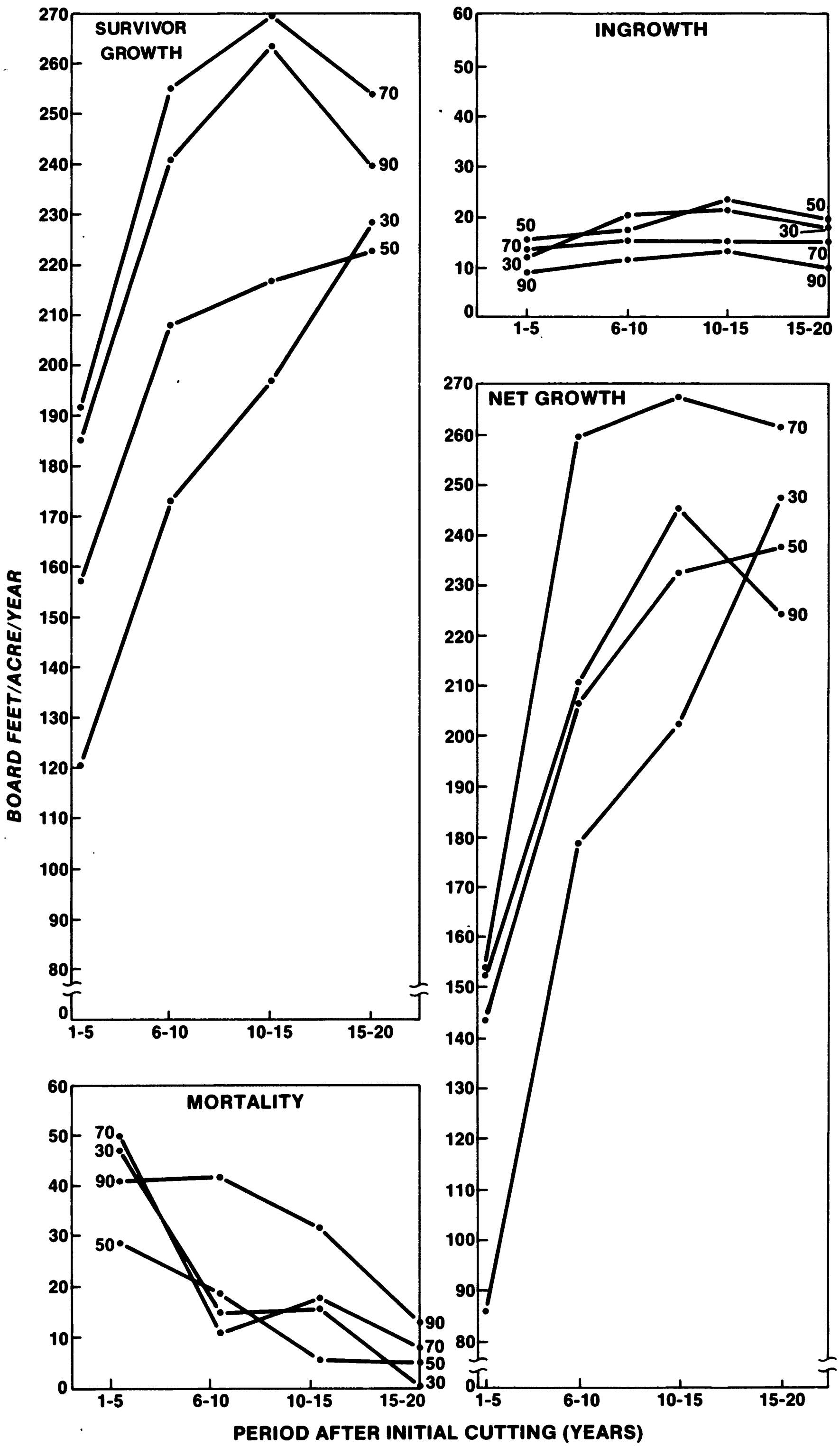

Figure 2.—*Average survivor growth, ingrowth, mortality, and net-growth (trees ≥ 9.6 inches d.b.h.) expressed as board feet (Scribner Decimal C)/acre/year by measurement year. Averages based on N=9 (three cutting cycles, three replications) for 50, 70, and 90 square feet; N=3 (one cutting cycle, three replications) for 30 square feet.*

Table 8.—*Average annual board foot growth (net per acre and standard deviation for trees 9.6 inches d.b.h. and larger by stocking level and measurement period) (Averages are based on N = 3 for 30 and N = 9 for 50, 70, and 90 square feet.)*

Stocking Level (ft²e/acre)	Measurement Period			
	1	2	3	4
	$\overline{X}$ (SD)—bd ft/acre/yr (Scribner rule)			
30	89(77)	178(42)	202(13)	247(26)
50	143(42)	206(52)	232(34)	237(44)
70	153(61)	259(39)	267(35)	261(41)
90	152(64)	210(76)	245(37)	224(40)

inch trees grew at maximum rates from 3.6 to 7.1 inches while 18-inch trees ranged from 4.2 to 5.8 inches d.b.h. growth. Value increase occurring from maximum growth rates could be substantially higher than those reported by Godman and Mendel (1978). Thus, the most vigorous trees should remain in the stand.

Jacobs (1968) illustrated the gradual diameter increase in similar stands over several decades of partial cutting. Average and perhaps maximum rates would be expected to change similarly in this study.

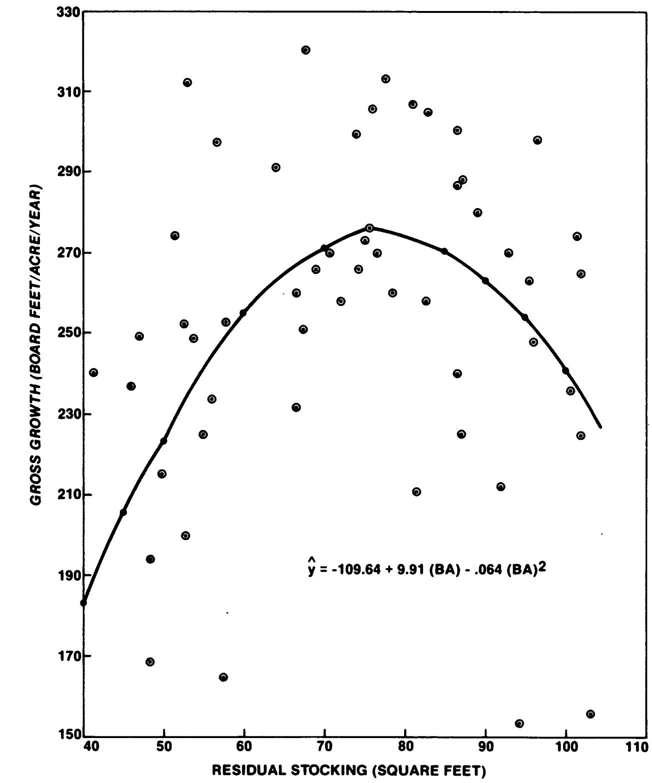

Figure 3.—*Plots of board foot gross growth for the best and worst growing periods (excluding the first period) for each replication. Curve represents best regression fit between residual basal area (square feet) and gross growth in board feet.*

Cut vs. Growth

When board foot cut was compared with board foot growth (table 10), the cut was proportionately less in more heavily stocked stands and longer cutting cycles. Apparently, stands cut more heavily and at shorter intervals are becoming balanced more rapidly due to faster ingrowth and reduced saw log mortality. As management proceeds, all cycles and treatments should result in balanced stands capable of sustaining cuts nearly equal to growth; however, the more lightly cut stands on longer cycles will take longer to reach a balanced structure.

Board foot cut (no deduction for cull) tended to be greatest for stands under the 5-year cutting cycle (table 10). Those treatments with cuts of 175 board feet or less were due partly to undercutting, thus stands under 10- and 15-year cycles were nearly equal.

Stand Structure and Stocking

The hypothetical stands used to test the interaction of structure and stocking on growth are given in table 11. Projections for the total stand (≥ 4.6 inches d.b.h.) in figure 4A indicated declines in basal area growth with increasing stocking levels and q values. The growth trends with increasing stocking corroborated trends measured for trees 4.6 inches d.b.h. and larger during the last two study growth periods (fig. 1). At low stocking levels (30 and 50), maximum growth rates in the simulated stands occurred at 1.2 (q), although differences in growth rates were not great for q's of 1.1 to 1.3. At higher stocking levels (70 and 90), substantial declines in growth rates resulted at q values 1.3 and 1.4.

Mortality was primarily responsible for differences in figure 4A. Mortality was especially heavy in the pole-timber class at 70 (1.4), 90 (1.3), and 90 (1.4), where smaller size classes suffered in overstory competition. A net growth decline resulted. As measured by number of trees, ingrowth increased substantially with lower stocking and q factor, but differences were not significant in terms of basal area during the 20-year simulation. Survivor growth varied little by q factor and stocking level.

Table 9.—*Average and maximum 20-year diameter growth of sugar maple under various densities, cutting cycles, and beginning diameters*
(In inches)

Cutting cycle	Stocking density/acre (trees 9.6 inches d.b.h. and larger) 30			50			70			90		
	Beginning diameter (inches)											
	6	12	18	6	12	18	6	12	18	6	12	18
AVERAGE												
5				4.3	4.2	4.0	3.5	3.3	3.1	2.7	2.7	2.8
10				3.9	3.9	3.8	3.2	3.2	3.2	2.3	2.5	2.6
15				3.9	3.5	3.2	3.1	3.2	3.3	2.4	2.5	2.6
20	4.0	3.8	3.7									
MAXIMUM												
5				6.9	6.1	5.8	5.7	5.1	4.6	8.4	5.1	4.0
10				6.3	6.5	5.0	5.8	7.1	5.0	5.6	4.9	3.7
15				7.1	5.6	4.2	7.1	5.7	4.6	3.9	3.6	5.1
20	7.0	6.8	3.8									

Table 10.—*Board foot harvest on an annual basis and board foot harvest as a percent of net growth by stocking level and cutting cycle*

Cutting cycle (years)[1]	Stocking level (square feet/acre) 50	70	90
HARVEST (bd ft/acre/year (SCRIBNER RULE))			
5	198	251	188
10	188	171	151
15	174	183	134
HARVEST AS PERCENT OF GROWTH			
5	96	100	61
10	95	74	69
15	79	70	52

[1]5- and 15-year cycles for 15-year period. 10-year cycle for 10-year period.

When considering sawtimber growth only (fig. 4B), maximum growth rates were obtained at two different stocking levels—structures, 70 (1.3) and 90 (1.2). Differences in growth rates were small at 50, 70, and 90 square feet at q's of 1.2 and 1.3 (fig. 4B), but declines in simulated sawtimber growth occurred at structures represented by q's equal to 1.1 and 1.4 (table 11). The projected decline at 70 (1.4) in figure 4B was a combination of high mortality in pole-size trees and the lack of saw log class ingrowth. At 50 (1.4), mortality was substantially less than for 70 (1.4) and at 90 (1.4), sawtimber growth (survivor growth) exceeded that at 70 (1.4), thus compensating for mortality and lack of ingrowth. In researching uneven-aged stand management, the development and stocking of the small size class, i.e., the saplings and poles, and the relation of their development to long-term productivity should receive greater emphasis.

In the field studies, application of existing marking rules (Eyre and Zillgitt 1953, Arbogast 1957) produced variations in size class distribution and maximum tree size by stocking level. Leaving 90 square feet of basal area resulted in a structure close to $q = 1.2$, with the greatest basal area stocking in the largest trees (20 inches d.b.h. +). Residual stands of 70 square feet in saw log trees approximated ($q \sim 1.3$) the structure recommended by Eyre and Zillgitt (1953). These stands had the greatest stocking in medium-sized saw logs and produced the maximum board foot growth (table 7). Stands with 50 square feet of residual basal area developed larger q values, and few study plots had trees greater than 24 inches d.b.h.

Recommendations for stocking and structure depend on management objectives. Where the goal is maximum total stand production, low residual stocking levels (30 or 50 square feet of basal area in saw log classes) provide optimal growth rates. Simulation procedures further suggest a low q value ($\sim q = 1.2$) for maximum stand growth. The distribution of trees and basal area by diameter class for 30 (1.2) is given in table 11.

Both field results and simulation indicated maximum sawtimber growth at the intermediate stocking

Table 11.—*Initial conditions used for testing the effects of stocking and structure on basal area growth (distributions were calculated using procedures outlined by Tubbs & Oberg (1978) assuming a maximum tree diameter of 24-inches)*

Size classes (inches)	q factors 1.1	1.2	1.3	1.4		1.1	1.2	1.3	1.4
	Number of trees/acre					Basal area (ft²/acre)			
					30/50[1]				
1.6- 4.5	14.7	27.5	46.2	72.2		0.8	1.4	2.4	3.5
4.6- 9.5	14.2	22.7	32.0	42.2		4.7	6.9	9.7	12.5
9.6-14.5	11.2	14.6	16.9	18.9		10.0	12.0	13.8	15.1
14.6-19.5	9.6	9.6	8.7	7.9		15.6	15.2	14.4	12.9
19.6-24.5	6.7	6.3	4.6	3.5		20.0	15.8	12.4	9.3
Stand total	56.4	80.7	108.4	144.7		51.1	51.3	52.7	53.3
					50/70				
1.6- 4.5	20.6	38.5	64.7	101.0		1.1	2.0	3.3	5.0
4.6- 9.5	20.7	31.8	44.6	59.3		6.5	9.9	13.5	17.6
9.6-14.5	16.5	20.4	23.9	26.4		13.8	16.8	19.4	21.1
14.6-19.5	12.8	12.9	12.0	11.1		21.5	21.4	18.0	18.1
19.6-24.5	10.3	8.2	6.4	4.9		28.0	22.2	17.1	13.1
Stand total	80.9	111.8	151.6	202.7		70.9	72.3	71.3	74.9
					70/90				
1.6- 4.5	26.5	49.5	83.2	129.9		1.4	2.6	4.2	6.4
4.6- 9.5	26.7	40.8	57.5	76.2		8.5	12.7	17.5	22.6
9.6-14.5	21.1	26.3	30.6	34.0		17.7	21.6	24.9	27.2
14.6-19.5	16.6	16.4	15.5	14.2		27.9	27.3	25.5	23.2
19.6-24.5	13.2	10.6	8.2	6.3		36.1	28.5	22.0	16.9
Stand total	104.1	143.6	195.0	260.0		91.6	92.7	94.1	96.3
					90/110				
1.6- 4.5	32.4	60.5	101.7	158.7		1.7	3.1	5.2	7.8
4.6- 9.5	32.5	50.0	70.3	93.0		10.3	15.6	21.3	27.7
9.6-14.5	25.9	32.1	37.4	41.5		21.6	26.5	30.4	33.1
14.6-19.5	20.2	20.1	18.9	17.4		34.0	33.4	31.1	28.3
19.6-24.5	16.0	12.9	10.1	7.7		43.5	34.8	27.1	20.5
Stand total	127.0	175.6	238.4	318.3		111.1	113.4	115.1	117.4

[1]Basal area (square feet) in sawtimber-sized trees/total stand basal area (square feet).

levels and q values, with little difference in sawtimber growth at 50, 70, and 90 square feet and q's of 1.2 and 1.3. Maximum growth occurred at 70 (1.3) and 90 (1.2). Based on our field measurements, however, the recommended structure and stocking for sawtimber growth is q = 1.3, with 72 square feet in sawtimber and 94 feet in the total stand ≥ 4.6 inches d.b.h. (table 12). This recommendation agrees closely to that proposed by Eyre and Zillgitt (1953) for uneven-aged northern hardwoods, but does not support the proposed stocking based on Adams' and Ek's (1974) work.

Using Ek's (1974) growth model, Adams and Ek (1974) projected diameter distributions that maximized several parameters of tree value as well as cordwood and board foot volume growth. Regardless of the parameter, the distributions had many more trees in the smaller diameter classes and fewer trees in the larger classes than recommended by Eyre and Zillgitt (1953). Our projections suggest very high mortality rates in the sapling, pole, and small saw log classes with structures recommended by Adams and Ek (1974). Projected over 20 years, these rates severely decreased stand volume growth. Some of these

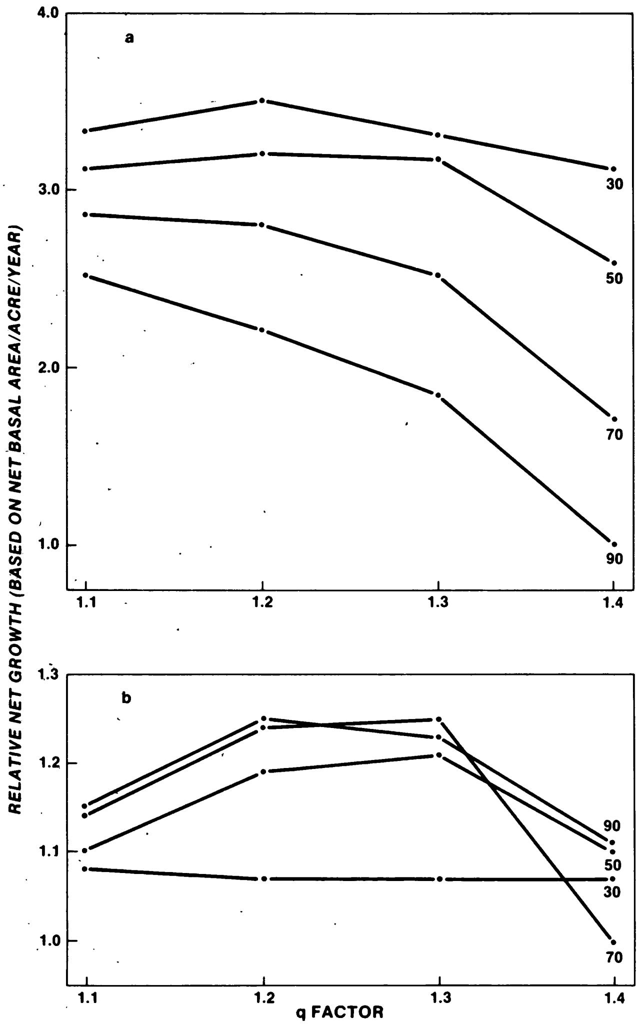

Figure 4.—*Optimization using a growth model to test the combined effects of stocking and structure on growth. Because predicted absolute growth rates were less important than the relative position of the response curves, values were plotted on a relative scale. (a) Average net annual basal area growth for all trees ≥ 4.6 inches d.b.h.; (b) Average net annual basal area growth for trees ≥ 9.6 inches d.b.h. Averages were based on a 20-year simulation; initial conditions for the model are given in table 11.*

differences are related to stand condition and composition. Ek's (1974) model was based on second-growth stands of at least 50 percent (basal area) sugar maple, along with yellow and white birch, aspen, northern red oak, and balsam fir. The mature stands in our study were predominantly sugar maple.

CONCLUSIONS

Our results suggest that stocking recommendations published by Eyre and Zillgitt (1953) are valid. Sugar maple stands on average or better sites (SI = 55 to 69) in northern Wisconsin and Michigan will produce saw logs at acceptable rates and develop a balanced structure when residual stocking is near 70 square feet in saw log trees (92 square feet for the entire stand) and harvest occurs every 10 years. At this stocking, annual growth rates should average 2.0 to 2.5 square feet of basal area/acre on average to better sites (trees ≥ 4.6 inches d.b.h.), 60 to 90 cubic feet/acre (trees ≥ 4.6 inches d.b.h.), and 200 to 300 board feet/acre (trees ≥ 9.6 inches d.b.h.).

Table 12.—*A comparison of growing stock distributions recommended for optimum sawtimber production in northern hardwood stands*

D.b.h. class (inches)	Present study[1] Number of trees/acre	Present study[1] Basal area (sq ft/acre)	Eyre and Zillgitt (1953) Number of trees/acre	Eyre and Zillgitt (1953) Basal area (sq ft/acre)	Adams and Ek (1974)[2] Number of trees/acre
1.6-4.5	83.2	4.2	202	8	—
4.6-9.5	57.5	17.5	65	16	149.1
9.6-14.5	30.6	24.9	28	22	79.8
14.6-19.5	15.5	25.5	17	26	15.4
19.6-24.5	8.2	22.0	8	20	0.7
Stand total	195.0	94.1	320	92	245.0 (>6"d.b.h.)

[1]Obtain from diameter distribution for 70 square feet of residual stocking in trees 9.6 inches and larger with a q = 1.3.
[2]Diameter distribution for optimal 5-year board foot growth; values were derived from 2-inch d.b.h. classes from 6 to 18 inches d.b.h.

Optimal growth at 70 square feet was the result of rapid survivor growth and low mortality. Maximum survivor growth occurred at 70 square feet. Stands at 30 square feet were clearly understocked for survivor growth. The importance of survivor growth was especially evident when considering board foot growth (table 7). Mortality was an important factor early in the study. Under managed conditions at the end of the study, however, mortality varied little by stocking level. Ingrowth accounted for a declining proportion of net annual growth with increasing stocking, and partially compensated for trends observed in survivor growth and mortality.

Near optimal growth rates, however, were obtained over a wide range of treatments and several structural and stocking combinations resulted in satisfactory growth during the 20-year measurement period. These combinations 70 square feet ($q = 1.3$) and 90 square feet ($q = 1.2$) in saw log trees, provide different management options. The lower density (70) favors faster growth, while the higher density (90) favors tree quality and form (Godman and Books 1971).

A short cutting cycle (e.g., 5 years) allows the harvest of trees normally lost to mortality at 15- or 20-year cycles. However, differences in net growth for 5-, 10-, and 15-year cycles were small and selecting among these cutting cycles should be based on practical considerations.

Optimal stocking and structure in this study were based on growth rates. Optimization based on value and economic return could provide different results. Because size, quality, and value are closely related, the greatest economic return may be produced by those stands whose structures include the greatest number of large trees. The fact that differences in growth at 50, 70, and 90 square feet were not large in a practical sense provides additional support for economic rather than biological factors in deciding which stocking to use.

ACKNOWLEDGMENT

A long-term study such as this is the product of many people's labor. The authors wish to give credit to Z. A. Zasada, F. R. Longwood, and R. M. Godman for developing and installing the study. We also wish to thank the field crews under the supervision of W. A. Salminen for managing and measuring the study areas. Credit is due D. G. Meister, Soil Conservation Service, for the soil survey and to J. Moser, Purdue University, for the computer summarizations of study data. T. W. Church and J. H. Cooley authored the 5- and 10-year progress reports, respectively, for the study. Both reports are on file at the Forestry Sciences Laboratory, Marquette, Michigan.

LITERATURE CITED

Adams, Darius M., and Alan R. Ek. 1974. Optimizing the management of uneven-aged forest stands. Canadian Journal of Forest Research 4:274-287.

Arbogast, Carl, Jr. 1957. Marking guides for northern hardwoods under the selection system. U.S. Department of Agriculture Forest Service, Station Paper 56, 20 p. U.S. Department of Agriculture Forest Service, Lake States Forest Experiment Station, St. Paul, Minnesota.

Church, Thomas W. 1960. Initial effect of residual stocking levels on basal area production in northern hardwood stands. U.S. Department of Agriculture Forest Service, Technical Note LS-581, 2 p. U.S. Department of Agriculture Forest Service, Lake States Forest Experiment Station, St. Paul, Minnesota.

Ek, Alan R. 1974. Nonlinear models for stand table projection in northern hardwood stands. Canadian Journal of Forest Research 4:23-27.

Erdmann, Gayne G., and Robert R. Oberg. 1973. Fifteen-year results from six cutting methods in second-growth northern hardwoods. U.S. Department of Agriculture Forest Service, Research Paper NC-100, 12 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Eyre, F. H., and W. M. Zillgitt. 1953. Partial cuttings in northern hardwoods of the Lake States. U.S. Department of Agriculture Forest Service, Technical Bulletin 1076, 124 p. U.S. Department of Agriculture Forest Service, Lake States Forest Experiment Station, St. Paul, Minnesota.

Gevorkiantz, S. R., and L. P. Olsen. 1955. Composite volume tables for timber and their application in the Lake States. U.S. Department of Agriculture Technical Bulletin 1104, 51 p. U.S. Department of Agriculture Forest Service, Lake States Forest Experiment Station, St. Paul, Minnesota.

Godman, Richard M., and David J. Books. 1971. Influence of stand density on stem quality in pole-size northern hardwoods. U.S. Department of Agriculture Forest Service, Research Paper NC-54, 7 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Godman, Richard M., and Joseph J. Mendel. 1978. Economic values for growth and grade changes of sugar maple in the Lake States. U.S. Department of Agriculture Forest Service, Research Paper NC-155, 16 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Jacobs, Rodney D. 1968. Growth and yield. In Sugar maple conference proceedings. p. 96-104. Aug. 20-22, 1968. Michigan Technological University, Houghton, Michigan.

Moser, John W., Jr. 1974. A system of equations for the components of forest growth. In Growth models for tree and stand simulation. J. Fries, ed. Royal College of Forestry, Research Note 30, p. 260-287, Stockholm, Sweden.

Moser, John W., Jr., Carl H. Tubbs, and Rodney D. Jacobs. 1979. Evaluation of a growth projection system for uneven-aged northern hardwoods. Journal of Forestry 77:421-423.

Solomon, D. S. 1977. The influence of stand density and structure on growth of northern hardwoods in New England. U.S. Department of Agriculture Forest Service, Research Paper NE-362, 13 p. U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania.

Trimble, G. R., Jr. 1968. Growth of Appalachian hardwoods as affected by site and residual stand density. U.S. Department of Agriculture Forest Service, Research Paper NE-98, 13 p. U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania.

Tubbs, Carl H. 1968. The influence of residual stand density on regeneration in sugar maple. U.S. Department of Agriculture Forest Service, Research Note NC-47, 4 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Tubbs, Carl H., and Robert R. Oberg. 1978. How to calculate size-class distribution for all-age forests. 5 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Crow, Thomas R., Carl H. Tubbs, Rodney D. Jacobs, and Robert R. Oberg.

1981. Stocking and structure for maximum growth in sugar maple selection stands. U.S. Department of Agriculture Forest Service, Research Paper NC-199, 16 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

The impacts of stocking, structure, and cutting cycle on basal area, cubic foot volume, board foot volume, and diameter growth are considered. Recommendations are provided for maximum growth in uneven-aged sugar maple stands.

KEY WORDS: *Acer saccharum*, uneven-age management, Lake States, stocking, stand structure, cutting cycle.

☆ U.S. Government Printing Office: 1981—767-169/4 Region No. 6