A Growth Model of Natural and Silviculturally Treated Stands of Even-aged Northern Hardwoods

by Dale S. Solomon

FOREST SERVICE GENERAL TECHNICAL REPORT NE-36
1977

FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE
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ABSTRACT

A computer programing system was developed which simulates the development and treatment of even-aged northern hardwoods in New England. The sapling phase begins with species distributions by quality classes. Natural mortality rates are applied, and a weeding option is available to select crop trees. A diameter distribution is generated for each species, and the smaller trees in the understory are dropped from the stand. The poletimber-sawtimber-harvest phase projects stand growth to any rotation age or diameter, using available stocking guides, yield-table data, and gross growth estimates. Thinning and final harvest yields are presented by species and quality classes. Using available data, the connecting phases of the simulator have been tested to determine the effects of silvicultural treatments (or lack of treatments) on long-term stand response.

The Author

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MANUSCRIPT RECEIVED FOR PUBLICATION 12 JULY 1976

PURPOSE AND SCOPE

The objective of the work described here was to develop a computer programing system that would simulate the development and treatment of an even-aged northern hardwood stand, beginning with a sapling stand and continuing through the harvest cut--a period of 100 years or more. Three considerations governed the approach to this task:

1. The biological and mensurational aspects of the problem incorporated as much of the available data as possible and attempted to avoid assumptions not fully documented by available data.

2. Through the use of Monte Carlo technique, I tried to include as much as possible of the unexplained variation that might affect the course of the process.

3. User options were programed as often as possible to include environmental conditions and silvicultural treatments.

The logic and data used to develop the simulation model are described elsewhere (Solomon 1974), but additional program information and comparisons of some examples are included here.

OVERALL MODEL

The overall model has two main phases: sapling stand development, and poletimber-sawtimber harvest. Each phase uses different variables and, most important, is controlled by a different analytical framework. To provide a basis for understanding the detailed descriptions in subsequent sections, a general overview of the purpose, logic, and makeup of each phase will be given.

SAPLING-STAND DEVELOPMENT PHASE

The development of sapling northern hardwoods has been described as a compound exponential process (Leak 1969a), where numbers of trees decrease rapidly and average diameter increases according to an inverted J-shaped (exponential) curve. This compound exponential process provides the basis for determining changes in numbers of stems by species groups during the sapling stage.

Available data on potential quality classes are inserted during this stage. When a weeding treatment is applied, the rate of mortality will change the shape of the exponential curve. Pruning will change the quality distribution of the stems in the residual stand.

The sapling stage ends at a mean stand diameter of 3.0 inches. At this point, understory trees are removed by 1-inch classes from consideration until the mean stand diameter is approximately 4.5 inches. The main overstory of the stand is then defined in terms of numbers of stems, by species and potential qualities. The model is then ready for the poletimber-sawtimber-harvest phase.

The primary sources of variability at this stage are initial numbers of stems, quality distribution of stems, species, and diameter distribution. Variation is expressed acre by acre as far as possible.

Poletimber-Sawtimber-Harvest Phase

The development of even-aged northern hardwood stands has been represented by stocking guides (Fig. 1) based on average stand diameter, numbers of trees, and basal area per acre (Solomon and Leak 1969). These guides apply to trees in the main crown canopy. A time span for this stocking chart is provided by available yield tables for northern hardwoods that provide estimates of the time required to reach a given mean stand diameter, by site class under both managed and unmanaged regimes.

Growth simulation begins with a program-supplied estimate of gross basal-area growth, dependent upon site index and age. Annual mortality at full stocking (A line) is determined from the stocking chart and yield-table data. Then, actual stand mortality is computed, based on the position of the stand between minimum stocking (B line) and full stocking, coupled with a random element. Given a mortality estimate, net basal-area increase is projected, and numbers of trees are reduced; then a new average stand diameter is computed.

The simulator maintains a record of numbers of trees, basal area, mean diameter, and percentage of stems by species and three quality classes.

Any of three thinning strategies can be employed by the user: thinning whenever the stand reaches the A line or 1/2 or 3/4 of the way between the A line and B line.

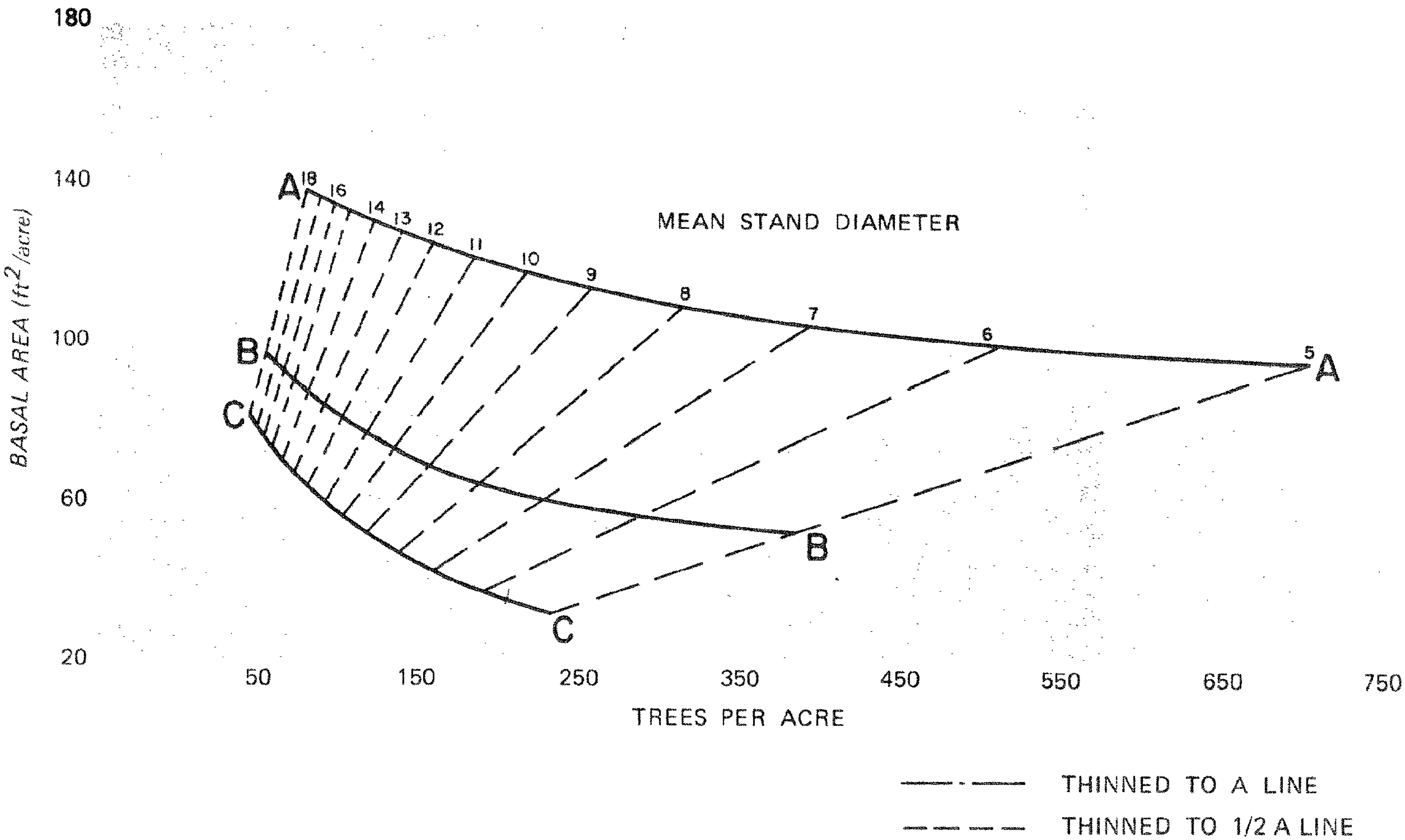

Figure 1.--Stocking guide for even-aged northern hardwood stands, showing basal area per acre, number of trees per acre, and mean dbh for trees in the main crown canopy. (From Leak et al. 1969).

The user can specify the order of removal of species and quality classes and delay the first thinning until a chosen mean diameter is reached. Under all strategies, thinning lowers the stocking to the B line.

Rotation can be specified by either stand diameter or age. At rotation, the stand is harvested and final yields are given, by species and qualities.

SAPLING-STAND COMPONENTS

The sapling-stand phase consists of five subroutines, two random-number generators, an input routine, and a main program. These combine into four steps: (1) determination of initial stem numbers and qualities, (2) computation of mortality patterns, (3) application of an optional cleaning treatment, and (4) determination of diameter distribution and elimination of understory trees.

Stem Numbers and Quality

The starting subroutine SAPST of the sapling-stand phase determines the number of stems in the stand at a mean diameter of 1.0 inches, as well as the proportion of stems by species with veneer, sawlog, and bulk-product potential.

Marquis (1967) gave evidence that species composition of hardwood stands is determined at an early age. Therefore data expressed as percentages will remain essentially constant for this phase of the simulator. Input for this subroutine comes from unpublished information[1] that indicates that a stand of 1.0 inch mean diameter averages 4,922 trees per acre, with a standard deviation of 779 trees. Subroutine SAPST draws an initial observation at random out of a normal distribution with this mean and standard deviation.

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[1]Leak, William B. Final report. Estimation of the exponential rate of tree dropout in young even-aged northern hardwoods. USDA For. Serv. Northeast. For. Exp. Stn., Durham, N. H., 10 pp., 1967.

A summary and evaluation of quality data in both young (Blum 1966, Gilbert 1965)[2] and old[3] stands provide the basis for estimating a range in potential stem qualities by species (Table 1). The subroutine picks rectangularly distributed numbers within the indicated ranges and sets these equal to the proportions of veneer, sawlog, and bulk quality stems.

Table 1.--Ranges in the percentage of stems in various potential product classes, by species

Species	Veneer	Sawlog	Bulk
Beech	5	8	87
Yellow birch	4 - 10	11 - 19	71 - 85
Sugar maple	3 - 5	12 - 27	68 - 85
Red maple	14	18	68
Paper birch	7 - 38	25 - 28	34 - 68
White ash	30	16	54

Mortality

Past work (Leak 1969a and 1969b) has shown that numbers of stems in a sapling northern hardwood stand decrease as stand diameter increases according to a negative exponential probability distribution, which has the form:

$$f(x)=re^{-rx}$$

Subroutine RPAR provides estimates of the negative exponential parameter "r" for commercial stems alone, and for all species together, and subroutine DROP applies mortality losses from an initial diameter of 1.0 inch to either the diameter at which weeding is applied or to the 3.0-inch mean diameter that marks the end of the sapling stage.

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[2]Marquis, David A. Progress report. Response of a 25-year-old northern hardwood stand to early thinning. USDA For. Serv. Northeast. For. Exp. Stn., Durham, N. H., 84 pp., 1967.

[3]Distribution of cubic-foot volume in old-growth stands by butt-log section and total tree volume. USDA For. Serv. Northeast. For. Exp. Stn., Durham, N. H., 1 p., 1956.

The average value of "r" for commercial species has been estimated at 0.4428, with 95 percent confidence intervals of 0.3746 to 0.4683. The average number of commercial stems is about 3,466 per acre, ranging from 1,698 to 5,234. Based on these values, if the actual number of commercial stems at 1 inch dbh (as determined by applying species percentage to the total stem numbers determined in SAFST) is greater than average (3,466), the estimated dropout parameter for the commercial species is estimated by simple proportions:

R(commercial)= .4428 + .0255 (commercial number -3,466) ÷ 1,768

If the actual number of stems is less than average:

R(commercial)= .4428 - .0682 (3,466 - commercial number) ÷ 1,768

Because of the relatively small amount of variation in total numbers of stems per acre, the negative exponential parameter for all species together may be taken as a constant of 0.5685.

Given the initial number (N_1), initial diameter (D_1), and the final diameter (D_2), the final number of stems of all species (N_2) is calculated in subroutine DROP from:

$$N_2 = N_1 \exp[r(D_1 - D_2)]$$

Multiplying the number (N_2) by the species and quality class proportions gives the number of trees per species and class.

CLEANING

A cleaning operation may be applied to the stand by subroutine CLEAN at any specified mean stand diameter between 1.00 and 3.0 inches. Numbers of crop trees, species priorities, and number of competitors to be removed per crop tree are also specified by the user. A low and a high number of good stems may be specified so that the potential and quality of the stand may be maintained.

Pruning may be applied to the first log of all yellow birches and sugar maples with grade 2 potential, thereby increasing their potential to grade 1.

From the desired number of crop trees and species priorities, subroutine CLEAN computes the actual number of crop trees. Only stems with grade 1 and 2 potential are considered as crop trees. Also, the number of stems to be removed is computed by multiplying the number of crop trees by the number to be removed per tree. It is assumed that the cut is proportional across all species and product classes, excluding those stems selected as crop trees.

The next step is to project the numbers of trees to the end of the sapling stage, by estimating the exponential number. This is done by comparing numbers of stems left after cleaning with the average numbers in an undisturbed stand. According to the stocking guide (Fig. 1), no mortality is expected if the number of stems is 400 or less. Therefore the exponential to apply after cleaning to project the final number of trees would be:

$$R = 0.4428 \text{ (residual remaining } -400.0)/(XN-400.0)$$

where XN = average number in an untouched stand for a given stand diameter and

$$\text{Log}_{10}\ XN = 4.016316 - 0.2273 \text{ (mean diameter)}$$

In projecting numbers of trees, no mortality losses are applied to crop trees. The negative exponential losses are applied only to those residual stems not classed as crop trees.

The final result from subroutine CLEAN is numbers of stems by species and quality classes at a mean stand dbh of 3.0 inches.

Diameter Distribution

In managing even-aged northern hardwoods beyond the sapling stage, silvicultural work is applied primarily to trees that make up the main crown canopy. Thus the subroutine DIAMD assigns trees to diameter classes and eliminates the understory trees. This step results in a loss in number of stems, an increase in average stand diameter, and changes in species composition.

Based on plot data from young stands of northern hardwoods about 3 inches in mean diameter,[4] observed range in the percentage of trees by diameter classes have been defined for three species groups: beech and sugar maple,

[4]Leak, William B., op. cit.

yellow birch-red maple-white ash, and paper birch and others (Table 2). Assuming about equal representation of each species group, the expected average diameter reflected by Table 2 is about 3.0 inches.

Table 2.--Range in percentage of trees in each diameter class for stands with 2.5- to 3.0-inch average diameter

Diameter class (inches)	Species		
	Beech and sugar maple	Yellow birch, red maple, and white ash	Paper birch and others
1	34 - 71	0 - 54	0 - 20
2	20 - 34	0 - 34	0 - 30
3	6 - 14	3 - 27	0 - 25
4	1 - 10	10 - 37	0 - 25
5	0 - 8	0 - 34	12 - 50
6	0 - 3	0 - 25	0 - 50
7	remainder	0 - 20	0 - 50
8		0 - 20	0 - 14
		remainder	remainder

Subroutine DIAMD shows a random observation within each range, and determines numbers of trees by diameter class and species. Then, the 1-, 2-, or 3-inch (cumulative) class is dropped so as to reduce the stand to 760 trees per acre or less; this procedure brings the stand into the lower end of the northern hardwood stocking guide (Fig. 1) at an average diameter of 5 to 6 inches. Many of the understory trees eliminated are beech and sugar maple. However, any beech or sugar maple designated as crop trees, and released by weeding, are not eliminated as understory.

Finally, the subroutine determines numbers of remaining trees by species and product class, as well as the final average diameter and basal area per acre. This information serves as input into the poletimber-sawtimber phase of the simulator.

The user is required to supply initial stand information and select silvicultural operations to be performed during the sapling phase.

The number of independent stands to be considered, stand titles, and the number of revolutions desired for each stand are required in the control program (UPTAKE). Also a random integer must be provided as an input into the rectangular (RANREP) and normal (GRASS) randon number generators.

The initial stand information needed is the site index and species composition. The site index is defined as height of sugar maple at base age 50, while species composition is expressed as a percentage of the initial stand at 1 inch dbh.

The possible silvicultural treatments are weeding and pruning operations. If weeding is desired, the user must supply beginning average stand diameter; upper and lower bounds or number of good stems, within which limits weeding will not be canceled; number of crop trees to be released; average number of competitors to remove per crop tree; and the crop tree priorities of beech, yellow birch, sugar maple, red maple, paper birch, and white ash.

The pruning option, if specified, will prune all yellow birch and sugar maple crop trees less than veneer grade to one log length.

Sapling MAIN Program

The sapling phase is monitored by a MAIN program, whose logic is illustrated in Figure 2. The program can be obtained from the National Technical Information Service.[5] The input consists of the six control cards for each stand as UPTAKE.

In addition to calling subroutines in the sequence shown, the MAIN program provides estimates of numbers of years required to reach the end of the sapling stage. These time estimates are based on site index and the application or nonapplication of weeding; computations are made by simple interpolation between the site index values tabulated below (Leak et al. 1969):

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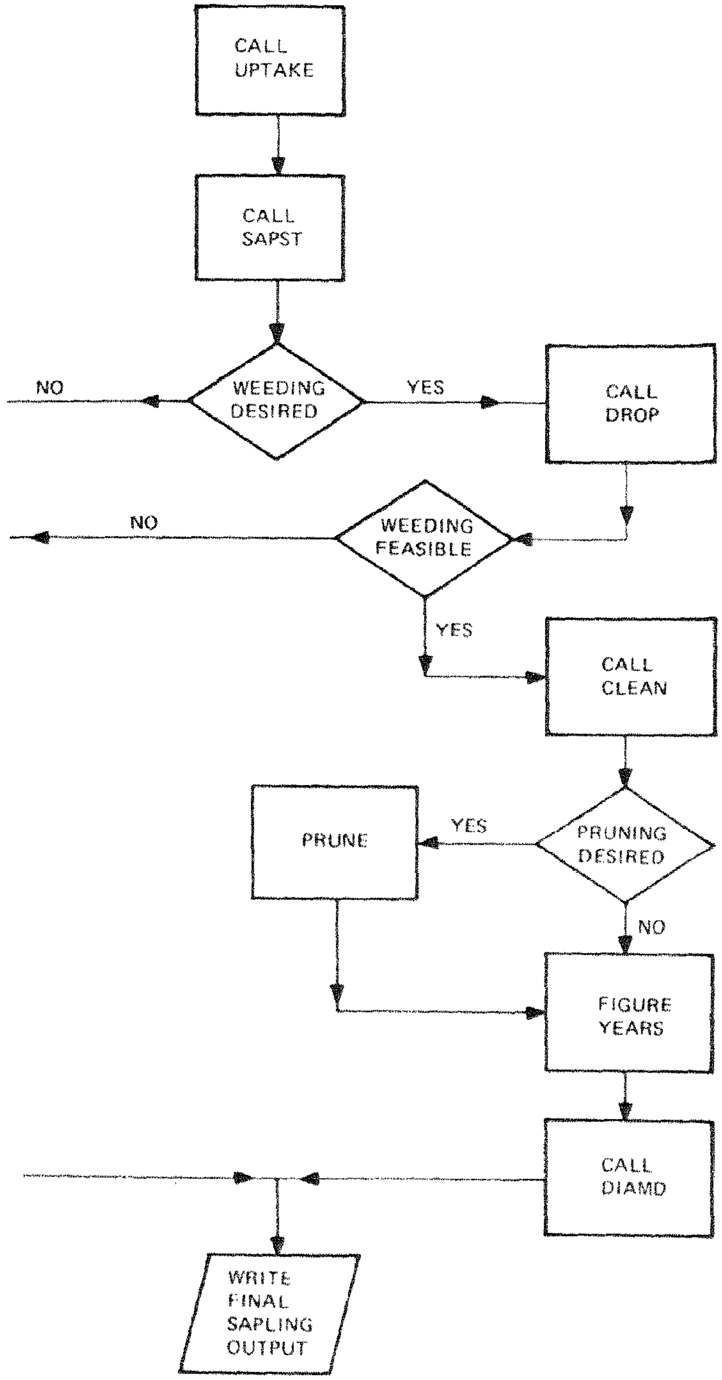
[5]Write U.S. Department of Commerce, National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161 and request National Technical Information Service (NTIS) Accession No. PB 269384 A/S; report number NEFES/77-5. NTIS magnetic tape price is $250.00. For further price information contact NTIS Input Branch, 703-557-4690.



ic of the MAIN program for the sapling phase.

Site Index (feet)	Weeded (years)	Unweeded (years)
50	44	59
60	38	50
70	33	44
80	29	40

SAPLING-STAND OUTPUT

An abbreviated example of the output from the sapling phase is shown in Figure 3; certain completion messages are not shown. If more than a single revolution for the stand is made, the output begins at the point of "WEEDING WAS APPLIED," or a comparable message. Each new stand starts at the head of a new page with the appropriate title.

The final output consists of: percent composition and number of stems for each species and quality class (for the important commercial species); a summary of total numbers of stems, basal area, and mean stand diameter; and an estimate of the years required to reach the end of the sapling phase. At this point or after several revolutions the stand information may be averaged and then used as input to the poletimber-sawtimber phase.

SAPLING PHASE EVALUATION

A summary of the final output from five runs of the sapling phase is given in Table 3. Each run reflects the average of eight revolutions. Two runs incorporated a weeding release of 200 crop trees per acre, two runs were without weeding, and the fifth included the pruning option. Both the weeding and no-weeding options were tested under disturbed and undisturbed site conditions. The disturbed site reflects the effect of a logging operation with the mineral soil exposed on less than 50% of the area. The undisturbed site produced consistently greater numbers of stems for all species and quality classes except for paper birch, which regenerates better on disturbed sites.

As might be expected, stocking in basal area is A line or above for the unweeded conditions, and somewhere between the A and B lines for the weeded (Fig. 1).

Numbers of good stems--quality 1 or 2--range from about 150 to 320. These numbers are in line with published information showing that numbers of crop trees in sapling

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UNDISTURBED WITH WEEDING SITE 50 NO PRUNING

 SPECIES COMP FOR  BE   YB   SM   RM   PB   WA   PC STMAP ASP  OTH  RMSPT
                 0.07 0.10 0.08 0.05 0.17 0.01 0.23 0.02 0.01 0.13 0.13

SITE INDEX =   50.0

WEEDING DESIRED AT DBH    2.500


WEEDING WAS APPLIED

CROP TREES OF BEECH  YEL B  SUG M  RED M  PAP B  W ASH    ALL
              0.0  117.9    0.0    0.0   82.1    0.0  200.0

NUMBER CUT IN WEEDING=    800.0     NUMBER LEFT=   1275.5
2-INCH CLASS DROPPED

SPECIES NUMBERS AFTER SAPLING STAGE

                       BEECH  YEL B  SUG M  RED M  PAP B  W ASH

    QUALITY  1           0.2   33.5    0.2    4.6   62.9    2.0
                        0.0%   5.4%   0.0%   0.7%  10.1%   0.3%

    QUALITY  2           0.4   15.1    1.0    5.9   65.8    1.0
                        0.1%   2.4%   0.2%   0.9%  10.6%   0.2%

    QUALITY  3           4.1   37.9    4.2   22.2  136.8    3.5
                        0.7%   6.1%   0.7%   3.6%  22.0%   0.6%

  RMSPRTS    ASPEN     OTHER      STR MAP    PIN C
  179.4      11.3       7.2        22.6       0.0
  28.8%      1.8%       1.2%        3.6%      0.0%

NUMBERS, BASAL AREA, AND AV DBH AT END OF SAPLING STAGE
    621.814      102.127       5.488

YEARS TO END OF SAPLING STAGE=       44.00
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Figure 3.--Example of the output produced at the end of the sapling phase.

Table 3.--Partial output at the end of the sapling phase for five combinations of site condition and treatment (average of eight trials each)

Site condition and treatment	Final dbh	Final basal area	Quality class	Number of commercial stems per acre by species and quality class: Beech	Yellow birch	Sugar maple	Red maple	Paper birch	White ash	All commercial stems
Disturbed site;	5.2	134.9	1	.5	14.5	.1	3.2	128.5	1.7	148.5
no weeding			2	.8	7.2	.4	4.2	157.7	.9	171.2
			3	8.5	30.0	1.5	15.6	309.1	3.1	367.8
Undisturbed site;	5.0	91.7	1	1.0	20.8	.8	5.3	54.3	2.3	84.5
no weeding			2	1.6	10.6	4.2	6.8	66.6	1.2	91.0
			3	16.8	44.4	17.0	25.8	130.4	4.1	238.5
Disturbed site;	5.0	103.4	1	.7	24.6	.1	3.0	134.5	1.6	164.5
weeding[a/] @			2	1.0	13.1	.5	3.9	118.2	.9	137.6
2.5 dbh			3	11.3	28.2	2.0	14.7	229.9	2.9	289.0
Undisturbed site;	4.6	71.5	1	1.3	34.3	1.1	4.7	73.1	2.0	116.5
weeding @ 2.5 dbh			2	2.0	18.5	5.8	6.1	55.9	1.1	89.4
			3	22.3	39.7	22.4	22.9	97.0	3.6	207.9
Weeding with	4.6	71.5	1	1.3	52.8	1.1	4.7	73.1	2.0	135.0
pruning			2	2.0	0.0	5.8	6.1	55.9	1.1	70.9
			3	22.3	39.7	22.4	22.9	97.0	3.6	207.9

[a/] Weeding consisted of the removal of an average of 4 competing trees around each of 200 crop trees of yellow birch and paper birch.

northern hardwoods may range from 50 to 100 or up to nearly 400 per acre (Blum and Filip 1962; Marquis 1967).

Total numbers of good stems are not consistently greater with weeding than with no weeding, although the trend is in that direction. Weeding favors quality class 1 at the expense of both other classes, but the numbers of good yellow birch and quality class 1 paper birch are consistently higher with weeding, primarily because these two species were favored as crop trees.

The numbers of good stems of the fast-growing paper birch and white ash are high in comparison with the percentage representation of these species in the initial regeneration. However, this is well in line with actual practice. Marquis (1967), for example, showed that paper birch and white ash accounted for 44 and 8 percent, respectively, of selected crop trees, but accounted for only about 12 and 3 percent, respectively, of the total number of commercial stems. The characteristic high quality and uniformly rapid growth rate (few understory stems) are the primary reasons for this phenomenon.

Weeding resulted in slightly smaller average diameter and basal area than no weeding at the end of the sapling stage. This reflects the higher proportion of tolerant and intermediate species brought about by the weeding treatments, as well as the somewhat smaller number of suppressed or understory trees that had to be eliminated from the stand. Estimated years to reach the end of the sapling stage were 44 with weeding and 59 years without weeding.

Pruning has no effect on diameter growth, basal area, or stand composition. The quality class 2 yellow birch crop trees were advanced to quality class 1 through pruning.

Because of the variability in the Monte Carlo technique, a range of responses will result over a series of runs. Therefore any one run may not follow the average evaluation described here.

POLETIMBER-SAWTIMBER-HARVEST COMPONENTS

The poletimber-sawtimber-harvest phase of the simulator grows the stand from the end of the sapling phase, approximately 4.5 inches average diameter, to harvest diameter or rotation age. The program covers four main steps: (1) growth projection, (2) thinning operations, (3) paper birch-aspen mortality, and (4) harvesting.

Growth Projection

The stand growth projection begins with gross growt as related to site index and age. Based on existing plc data and available yield tables (Leak et al. 1969), this relationship can be expressed as:

$$\text{Annual gross basal-area growth} = 0.06128+0.04333(\text{site})-0.00062(\text{age})-0.00002(\text{age}^2)$$

This equation is applicable for site indexes between 40 80 (for sugar maple, base age 50) and does not apply to young sapling-sized stands. Otherwise it maintains a relatively constant gross growth rate until the stand re the higher age classes.

Annual mortality is based on the northern hardwood stocking chart and yield table (Solomon and Leak 1969) expressed by:

Stocking chart:

$$\text{A-line number of trees} = 2111.07373 - 409.31909(\text{MS}$$
$$+ 28.65013(\text{MSD})^2 - 0.67964(\text{MSD})^3$$
$$+ 16.88345(\text{SIN}(\tfrac{\pi}{4}(\text{MSD}-1)))$$

$$\text{B-line number of trees} = 1111.72095 - 210.41010(\text{MS}$$
$$+ 14.68426(\text{MSD})^2 - .34898(\text{MSD})^3$$
$$+ 9.05404(\text{SIN}(\tfrac{\pi}{4}(\text{MSD}-1)))$$

Where MSD is the mean stand diameter.

Yield Table:

Years, Site 50 = 54.56725 - 7.011110 (D) + 1.65473

Years, Site 60 =-2.80710 + 8.95088 (D) + 0.29923 (

Years, Site 70 = 6.48904 + 5.98422 (D) + 0.26806 (

Where years is the years to reach a given mean stand diameter D.

For a given mean stand diameter, net annual basal area growth at the A line can be computed, and mortality at the A line is estimated by subtracting net growth from gross growth.

Our estimate of actual stand mortality is based on the assumption that mortality at minimum stocking (the B line) is zero, and that mortality of a stand above the B line is in some way proportional to its position between the A line and B line.

$$\text{Stand mortality} = \left(\frac{BA - BAB}{BAA + 5 - BAB}\right)^{X} \cdot (GG - BAGA)$$

Where BA = basal area of stand

BAB = basal area of B line

BAA = basal area at A line

GG = gross growth

BAGA = annual net basal area growth at A line

X = a random exponent between 1 and 1.5

When X = 1, mortality is computed in direct proportion to the position of the stand between the A line and B line. When X>1, the mortality rate increases as the A line is approached and passed--a phenomenon in line with general experience.

Unpublished data for mixed species of northern hardwoods have confirmed that the average diameter of trees that die equals the average stand diameter. After computing and subtracting the number of trees that die and projecting the net basal-area growth, the new average stand diameter for that year is calculated.

Growth is projected each year as described above until a thinning or harvest operation interrupts the process. After thinning, annual growth projections are resumed once again. Species and quality-class percentages are held constant throughout the growth-projection process, except for the accelerated mortality of paper birch and aspen described later. Experience has shown that although the species do not grow at exactly the same rate, species changes in the overstory of even-aged northern hardwoods proceed quite slowly (Leak 1961, Marquis 1967).

Thinning and Harvest Yields

In subroutine THIN the user may specify no thinning or the diameter at which to begin thinning. The stand wil be reduced to the B line whenever the stand reaches the specified stocking A line, 3/4 of the way from B line to A line, or 1/2 of the way from B line to A line.

Tree removal is specified by the user according to species and quality class. Since mortality of paper birch and aspen increases sharply from age 80 on, the program uses PBMORT to simulate the mortality unless the user specifies removal prior to age 70. Paper birch and aspen are the first species removed in the first thinning called after age 70.

The final harvest is specified by rotation age or mean stand diameter. Intermediate and harvest yields are readily converted to local volume standards since the output is presented as a percentage of the trees of each species and quality class at the specified mean stand diameter.

Paper Birch-Aspen Mortality

When the stand reaches 80 years of age, simulated mortality of any remaining paper birch and aspen is accelerated by subroutine PBMORT to represent the short life span of these two species. Five percent of the initi amount of each species is removed per year, resulting in complete removal of both species between 80 and 100 years of age. Mortality losses are applied proportionally acros all quality classes. Percentages of the remaining species are adjusted so that they continue to sum to 100 percent.

As mentioned earlier, the user has the opportunity to circumvent this accelerated mortality by specifying that paper birch and aspen be removed in the first thinning after age 70.

CONTROL PROGRAMS

Poletimber - Sawtimber - Harvest Input Requirements

The user specifies the starting parameters for each stand (output from the sapling phase) and his options for controlling the treatments during this phase of the simulation. The logic for this phase is illustrated in Fig

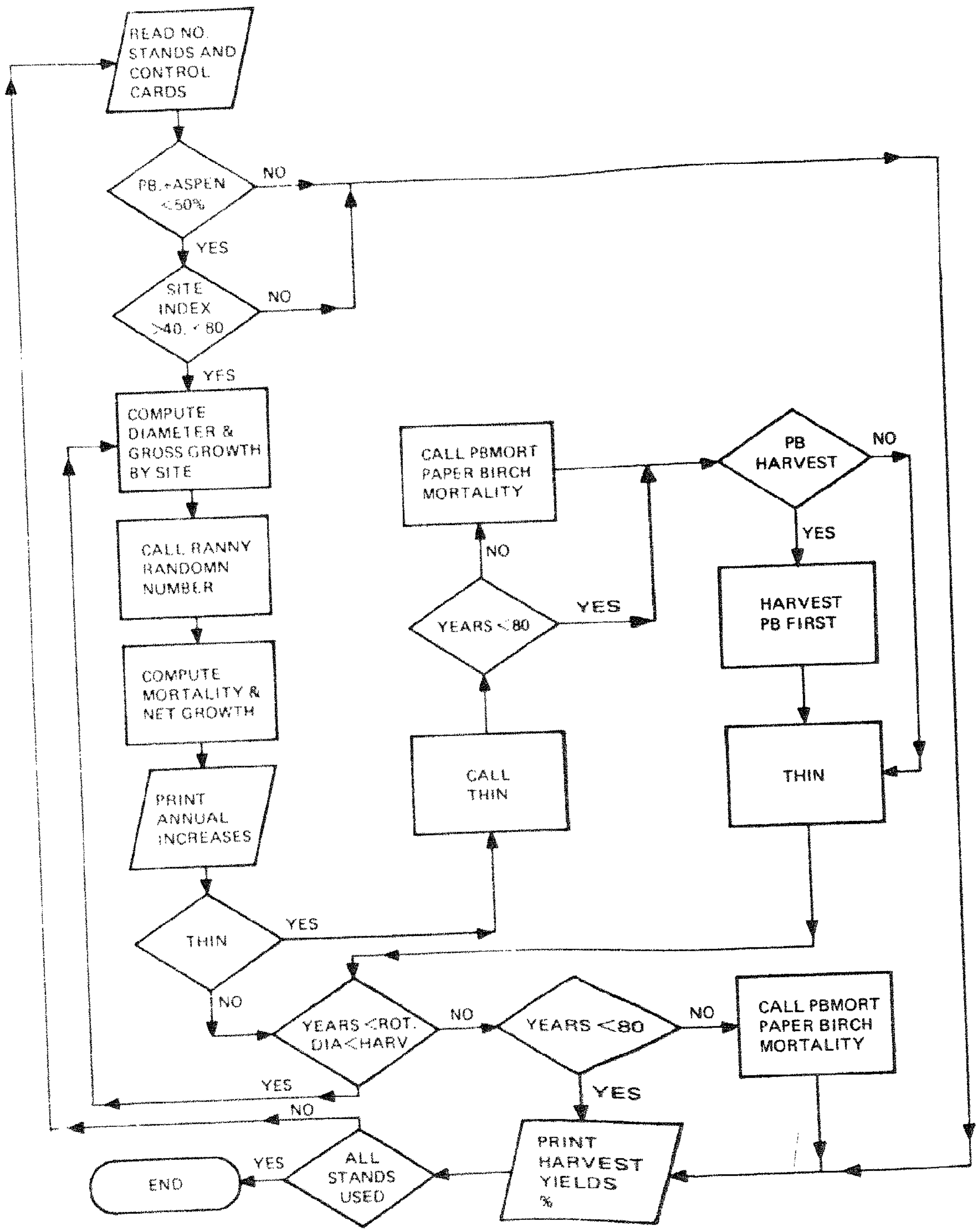

Figure 4.--Logic of MAIN program for poletimber-sawtimber-harvest phase.

Basic stand data to start the program are needed. The site index, age, and stand density (basal area, number of stems/acre, and average stand diameter) must be included. The species composition is listed by percentages in three quality classes and eight species groups: beech, yellow birch, sugar maple, red maple, paper birch-aspen, white ash, conifers, and others.

As each stand matures, treatment decisions are required. To simulate silvicultural practices, the density level used to initiate thinning, thinning intensities, paper birch salvage operations, and species priorities for removal must be specified by the user.

Harvest information is needed for stand rotation in the form of desired stand diameter and/or age limits.

Poletimber-Sawtimber-Harvest Output

A condensed version of the output for the poletimber-sawtimber-harvest phase is shown in Figure 5. Some of the error or completion messages are not shown.

More than one set of stand conditions may be entered with each run, but it is necessary to supply a complete set of control cards for each stand. The first set of output is for the first control set, and so on until all control sets are used. No further data are needed.

The first block of output lists all the input conditions for this numbered stand. These include site, number of trees per acre, basal area, mean stand diameter, age of the stand, species composition by quality class, the order of priority removal for these classes, diameter at which to start thinning, user of machine removal of paper birch-aspen, when to thin the stand, and the rotation age or harvest diameter. These provide a check on the control cards for this stand.

Annual information is printed so that the growth of the stand can be traced. This information includes the age of the stand, the mean stand diameter, number of trees and basal area per acre. Also given are the number of trees and basal area for the A and B lines. The annual printout continues until the mean stand diameter at which to start thinning--if any--has been reached. The number of trees to be thinned is printed. For each thinning, the number of trees and the percentage by species of the total stand thinned are listed by species and quality class.

```
POLETIMBER SAWTIMBER SIMULATOR

STAND NUMBER    1  STARTED WITH

   SITE = 50.
    NUMBER OF TREES/ACRE =  665.
    BASAL AREA/ACRE =  91.67
    DIAMETER =  5.0
    AGE OF STAND =  59.

QUALITY                SPECIES
 CLASS     BE     YB     SM     RM    PBA     WA    CON  OTHER
  1      0.1%  3.1%  0.1%  0.8%  8.2%  0.4%  0.0%  0.0%
         0.7  20.6   0.7   5.3  54.5   2.7   0.0   0.0

  2      0.2%  1.6%  0.6%  1.0% 10 0%  0.2%  0.0%  0.0%
         1.3  10 6   4.0   6.6  66.5   1.3   0 0   0.0

  3      2.5%  6.7%  2.5%  3.9% 21.3%  0.6%  0.0% 36.2%
        16.6  44.6  16 6  25.9 141.6   4.0   0.0 240.7

ORDER OF SPECIE CLASS REMOVAL BY PRIORITY
 24  23  22  21  20  19  18  17  16   9  12  13  14  15
     11  10   8   1   4   6   5   7   3   2

   ITHIN = 1,THIN WHEN STAND REACHES      A-LINE
   OPERATER CONTROLS PAPER BIRCH REMOVAL PRIORITY
   DIAMETER AT WHICH THINNING STARTED =  6.0
   ROTATION AGE =  150.
   HARVEST DIAMETER =  14.0


 MEAN DIAMETER FOR AGE      60. =    5.086

 NUMBER OF TREES IN STAND =  660.34
      A-LINE NUMBER OF TREES   PRESENT =  679.8 NEXT YR. =    661.6
      B-LINE NUMBER OF TREES   PRESENT =   374.9 NEXT YR. =    365.5

 BASAL AREA OF STAND =   93.16
      BA AT A-LINE =   95.91
      BA AT B-LINE =   52.89


 THINNING NO.     1
 NUMBER OF TREES THINNED= 246.731
AVERAGE STAND DIAMETER =   6.01

QUALITY               SPECIES
CLASS     BE     YB     SM     RM    PBA     WA   CON  OTHER
  1      0.0%  0 0%  0.0%  0.0%  0.0%  0.0%  0.0%  0.0%
         0.0   0 0   0.0   0.0   0.0   0.0   0.0   0.0

  2      0 0%  0.0%  0.0%  0.0%  0.0%  0.0%  0.0%  0.0%
         0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

  3      0.0%  0.0%  0.0%  0.0%  8 4%  0 6%  0.0% 36.2%
         0.0   0.0   0.0   0.0  46.00  3.27  0.0 197.46

 STAND NUMBER      1  AT HARVEST DIAMETER   14.0 OR ROTATION AGE 150.0
 SITE INDEX =  50.
 NUMBER OF TREES/ACRE = 119.4
 BASAL AREA =  94.22
 MEAN STAND DIAMETER =  12.0
 AGE OF STAND =   150.
 THINNING BEGAN AT DIAMETER =    6.0


              HARVEST YIELD IN PERCENT

'UALITY                SPECIES
 CLASS     BE     YB     SM     RM    PBA     WA    CON  OTHER
  1      0.7% 20.8%  0.7%  5.4%  0.0%  2.7%  0.0%  0.0%
         0.8  24.8   0.8   6.4   0 0   3.2   0.0   0.0

  2      1.3% 10.7%  4.0%  6.7%  0.0%  1.3%  0.0%  0.0%
         1.6  12.8   4.8   8.0   0.0   1.6   0.0   0.0

  3     16.7% 29.0%  0.0%  0.0%  0.0%  0.0%  0.0%  0.0%
        20.0  34.7   0.0   0.0   0.0   0.0   0.0   0.0
```

Figure 5.--Example of output at the end of the poletimber-sawtimber-harvest phase.

The stand continues to be thinned at the specified interval, when it reaches either 1/2 the distance between the A and B lines, 3/4 of the distance between the A and B lines, or the A line. The final listing of all stand conditions plus the species numbers and percentages by quality classes is the last printout at rotation age or harvest diameter.

POLETIMBER-SAWTIMBER-HARVEST PHASE EVALUATION

Using the test runs outlined in the sapling phase as input for the poletimber phase, various management intensities, sites, and silvicultural practices were chosen and the results compared. This evaluation will show the range of information obtained from the model and give an indication of the simulated response to a variety of management options. Table 4 outlines the options used and the resulting yields, age, and mean stand diameter. Stand composition is detailed in Table 5, while Table 6 summarizes harvest volumes by species and quality classes of: (1) veneer, (2) sawlogs, and (3) pulpwood.

Management intensities were selected by thinning at the A line (less intense) or at 1/2 A line (very intense). By increasing the level of management on the same site the mean annual yield was increased by 25 percent as the thinnings were able to utilize a greater percentage of the mortality and increase growth on the remaining trees (Table 4). As a result of this increased diameter growth, the yield of quality class 1 was increased approximately 80 percent with increased management regardless of weeding treatment from sapling phase (Table 6).

However the percentage increase was greater on the better sites, reflecting the superior response to silvicultural treatment by these sites. Comparing the growth of two stands on the same site (Fig. 6) shows the increased yields and final size that can be achieved when intensive management (thinning at 1/2 A line) is selected.

The effect of site index was studied at sites with indexes of 50 and 70 (sugar maple, base age 50). The difference in site index had no consistent effect on species composition (Table 5); or quality class (Table 6); however the mean annual yield was approximately 100 percent greater on the better sites, with the less intensely managed stands showing the greatest effect (Table 4).

Operation		Without weeding: Site index 50		Without weeding: Site index 70		With weeding: Site index 50		With weeding: Site index 70			
		1/2 A[a]	A[b]	1/2 A	A	1/2 A	A	1/2 A	A	A PB Harv.	A Pruning
Thin 1	Volume (ft^3)	851	851	1159	1159	757	802	1034	1123	1123	1123
	Age (years)	76	76	56	56	56	71	49	54	54	54
	Mean diam. (in)	6.01	6.01	6.33	6.03	6.30	6.38	6.07	6.53	6.53	6.53
Thin 2	Volume	416	963	575	1376	403	1014	555	1377	1388	1377
	Age	91	139	66	99	80	140	59	96	96	96
	Mean diam.	7.44	10.73	7.42	11.65	7.36	11.75	7.47	12.29	12.29	12.29
Thin 3	Volume	424	--	587	--	432	--	610	--	--	--
	Age	108	--	76	--	95	--	69	--	--	--
	Mean diam.	9.01	--	9.00	--	8.99	--	9.06	--	--	--
Thin 4	Volume	494	--	699	--	491	--	662	--	--	--
	Age	126	--	89	--	115	--	82	--	--	--
	Mean diam.	11.21	--	11.25	--	11.24	--	11.33	--	--	--
Thin 5	Volume	505	--	659	--	492	--	679	--	--	--
	Age	143	--	99	--	131	--	92	--	--	--
	Mean diam.	13.17	--	13.13	--	13.14	--	13.22	--	--	--
	Volume	2346	2189	3371	3861	2369	2318	3306	3629	3621	3629
	Age	149	150	103	112	137	150	95	104	104	104
	Mean diam.	14.1	12.1	14.2	14.1	14.1	13.0	14.1	14.0	14.0	14.0
Total volume removed		5036	4003	7050	6396	4944	4134	6846	6129	6132	6129
Mean annual yield (ft^3 /year)		33.80	26.69	68.45	57.11	36.09	27.56	72.06	58.93	58.96	58.93

[a] Thinned to 1/2 A line; [b] Thinned to A line

Table 5.--Species composition of stand at harvest

Species		Without weeding				With weeding				
		Site index 50		Site index 70		Site index 50		Site index 70		
		A[a]	1/2 A[b]	A	1/2 A	A	1/2 A	A	1/2 A	A line with FB harvest
Beech	% comp	18.7	13.3	18.0	1.4	21.5	2.0	21.1	2.1	18.3
	Vol. (ft^3)	409	311	694	47	498	66	765	69	663
Yellow birch	% comp	60.7	52.2	62.1	64.3	60.6	84.8	61.2	78.6	66.9
	Vol.	1328	1225	1298	2167	1404	2803	2219	2598	2422
Sugar maple	% comp	4.7	7.8	4.5	9.6	5.7	2.2	5.6	2.1	5.3
	Vol.	102	163	174	324	132	55	203	69	192
Red maple	% comp	12.0	20.0	11.5	16.5	9.4	8.0	9.3	8.3	8.1
	Vol.	263	469	444	556	218	190	337	274	293
Paper birch	% comp	0	0	0	0	0	0	0	5.3	0
	Vol.	0	0	0	0	0	0	0	195	0
White ash	% comp	4.0	6.6	3.9	8.2	2.6	3.0	2.5	3.1	2.2
	Vol.	88	155	151	276	[illegible]	71	91	102	80

Table 6.--Final harvest volume (in cubic feet) by species and quality class

Species	Qual. class	Without weeding						With weeding							
		Site index 50			Site index 70			Site index 50			Site index 70				
		Initial	A[a]	1/2 A[b]	Initial	A	1/2 A	Initial	A	1/2 A	Initial	A	1/2 A	PB Salvage	Prun-ing
Beech	1	2	15	25	2	23	47	3	23	66	4	36	69	33	36
	2	3	28	52	4	50	0	4	37	0	5	54	0	47	54
	3	38	366	234	53	621	0	46	438	0	64	675	0	583	675
Yellow birch	1	47	453	507	66	772	1429	70	670	1815	98	1030	1884	834	1593
	2	24	234	418	34	398	738	38	364	988	53	562	714	489	0
	3	102	641	0	143	128	0	81	370	0	114	527	0	1039	627
Sugar maple	1	2	15	26	2	23	47	3	23	66	4	36	69	33	36
	2	9	98	157	13	151	276	11	109	7	16	167	0	145	167
	3	38	0	0	53	0	0	46	0	0	64	0	0	14	0
Red maple	1	12	115	209	17	197	371	10	97	264	14	149	274	130	149
	2	15	147	258	21	247	185	13	121	0	18	189	0	163	189
	3	59	0	0	83	0	0	47	0	0	66	0	0	0	0
Paper birch	1	125	0	0	175	0	0	150	0	0	210	0	195	0	0
	2	152	0	0	213	0	0	114	0	0	160	0	0	0	0
	3	325	0	0	456	0	0	216	0	0	303	0	0	0	0
White ash	1	6	59	103	9	100	185	4	37	99	5	54	102	47	54
	2	3	28	52	4	50	91	3	23	0	4	36	0	33	36
	3	9	0	0	13	0	0	8	0	0	11	0	0	0	0
Other	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	553	0	0	774	0	0	405	0	0	568	0	0	0	0

[a] Thinned to A line; [b] Thinned to 1/2 A line

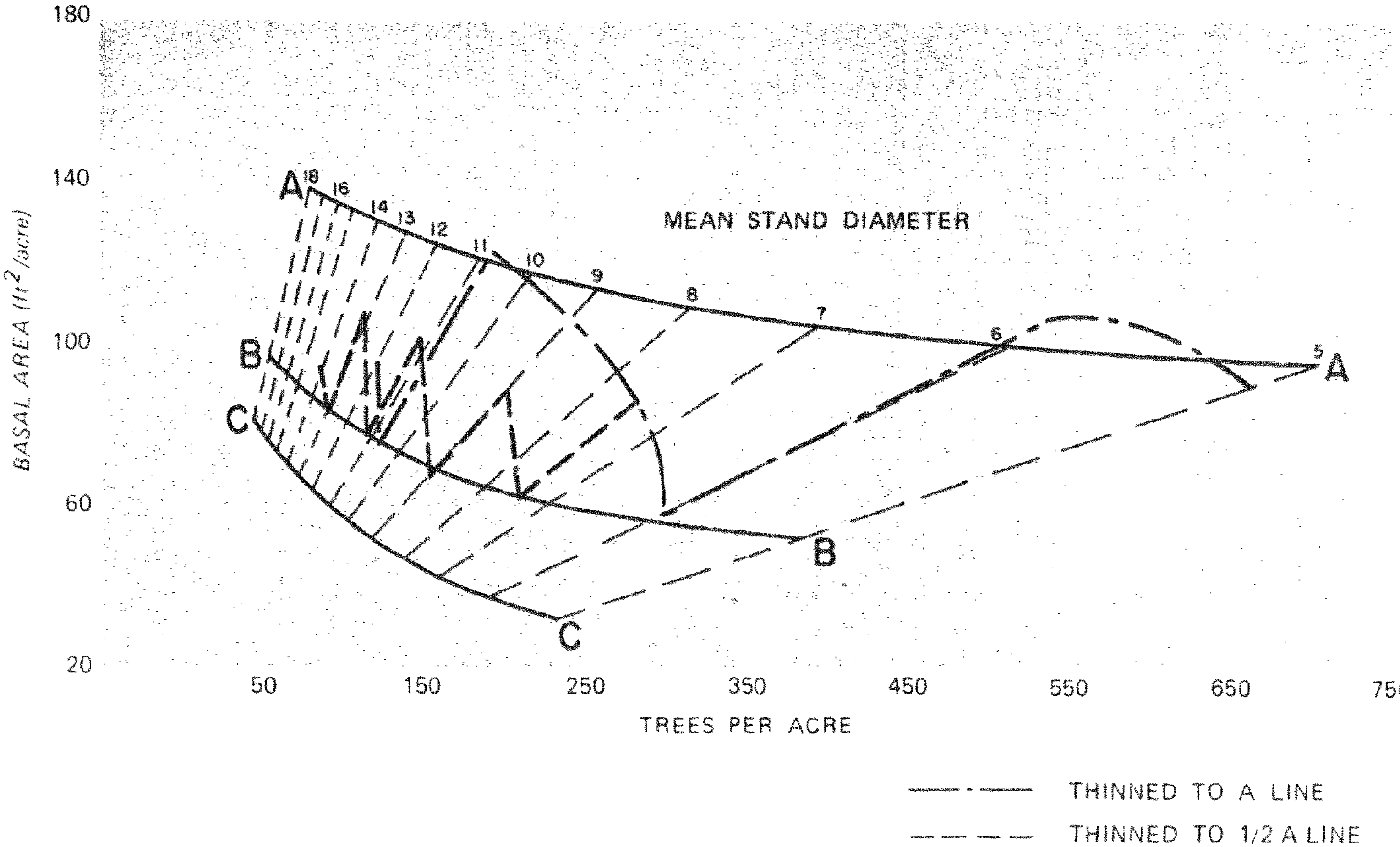

Figure 6.--A comparison of A-line versus 1/2 A-line thinning for unweeded stands on site index 50.

The better site also required 40 years less to reach the same mean stand diameter (Fig. 7).

The model indicates that stands on better sites respond more rapidly to silvicultural treatment through early mortality, crown differentiation, and increased volume growth (Leak et al. 1969).

Weeding or not weeding in the sapling phase was also evaluated through the poletimber-sawtimber-harvest phase. Weeding had a minimal positive effect over not weeding. Only a few years separated the stands at harvest age (Fig. 8), and the mean annual yield increased slightly (Table 4). The most significant effect was the improvement in quality by 50 percent, which occurred on the poorer sites (Table 6). There was very little effect on the percentage of primary crop species (yellow birch and sugar maple) on the less intensely managed stands. On more intensely managed stands the primary crop species were greatly favored at the expense of nearly all others.

Therefore weeding in sapling-size stands offers very little improvement in yield or length of stand rotation, regardless of site, but weeding in young stands <u>will</u> improve the quality and quantity of desired species.

Returning the stocking to the B line by harvesting the paper birch in the first thinning after age 70 instead of letting it die increased the yield of paper birch of quality classes 1 and 2 at the second thinning, but it was removed instead of yellow birch in quality class 3 (Table 7). (Both could not be removed without lowering the stocking below the B line.) This resulted in an increase of 40 percent in class 3 yellow birch, reducing the yield at harvest of the upper classes of yellow birch by 13 percent each, and the yields of all other quality classes and species by an average of 12 percent. Harvesting paper birch increased by 95 percent the total paper birch obtained. Knowing this, the manager can weigh the trade-offs of increased paper birch, and class 3 yellow birch, versus a decrease in all other classes and species.

The pruning option was also tested; its only effect was to move quality class 2 of the pruned species into class 1 with no effect on growth or final yield.

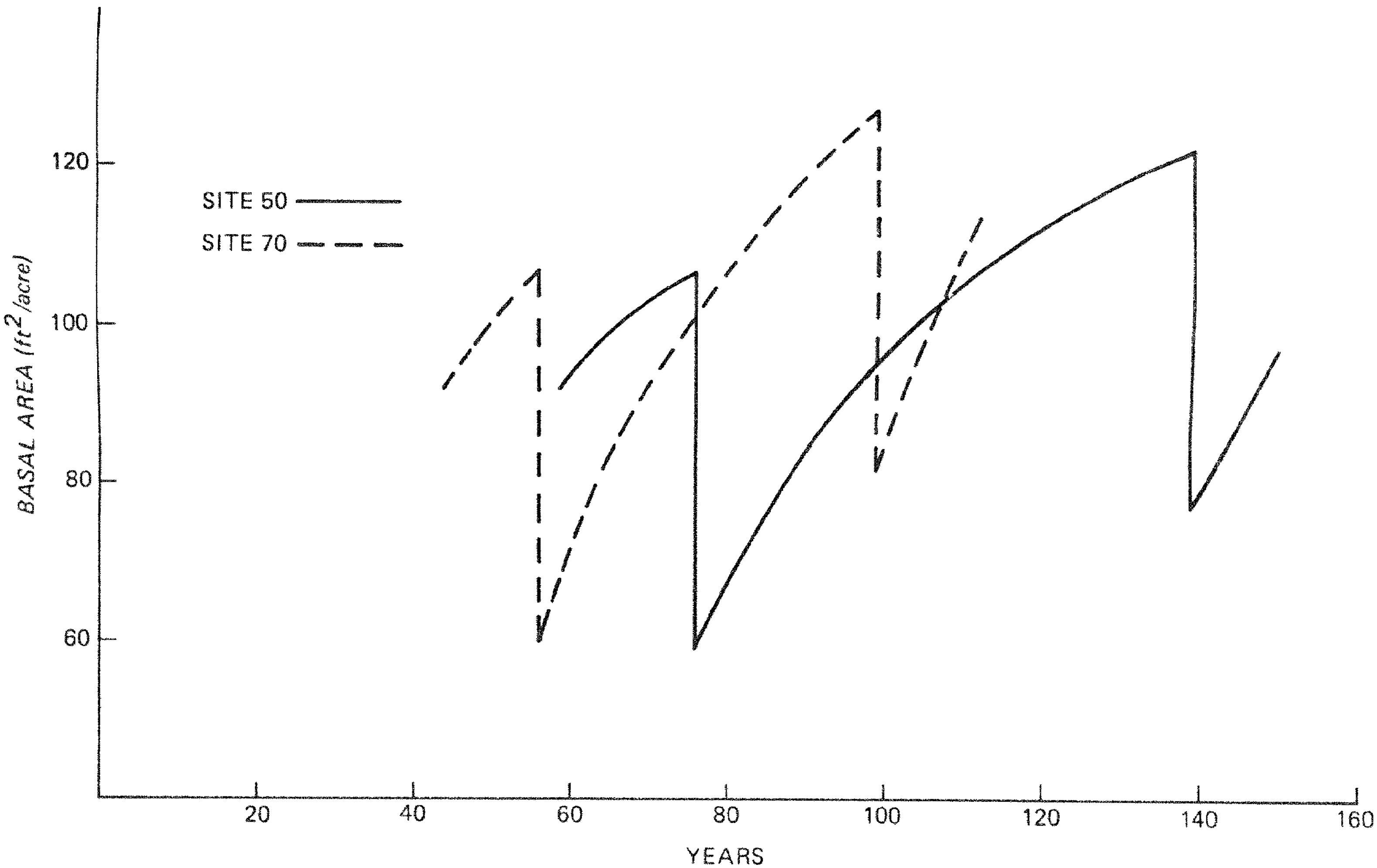

Figure 7.--Basal area response over time to A-line thinning of unweeded stands with site index 50 versus those with site index 70.

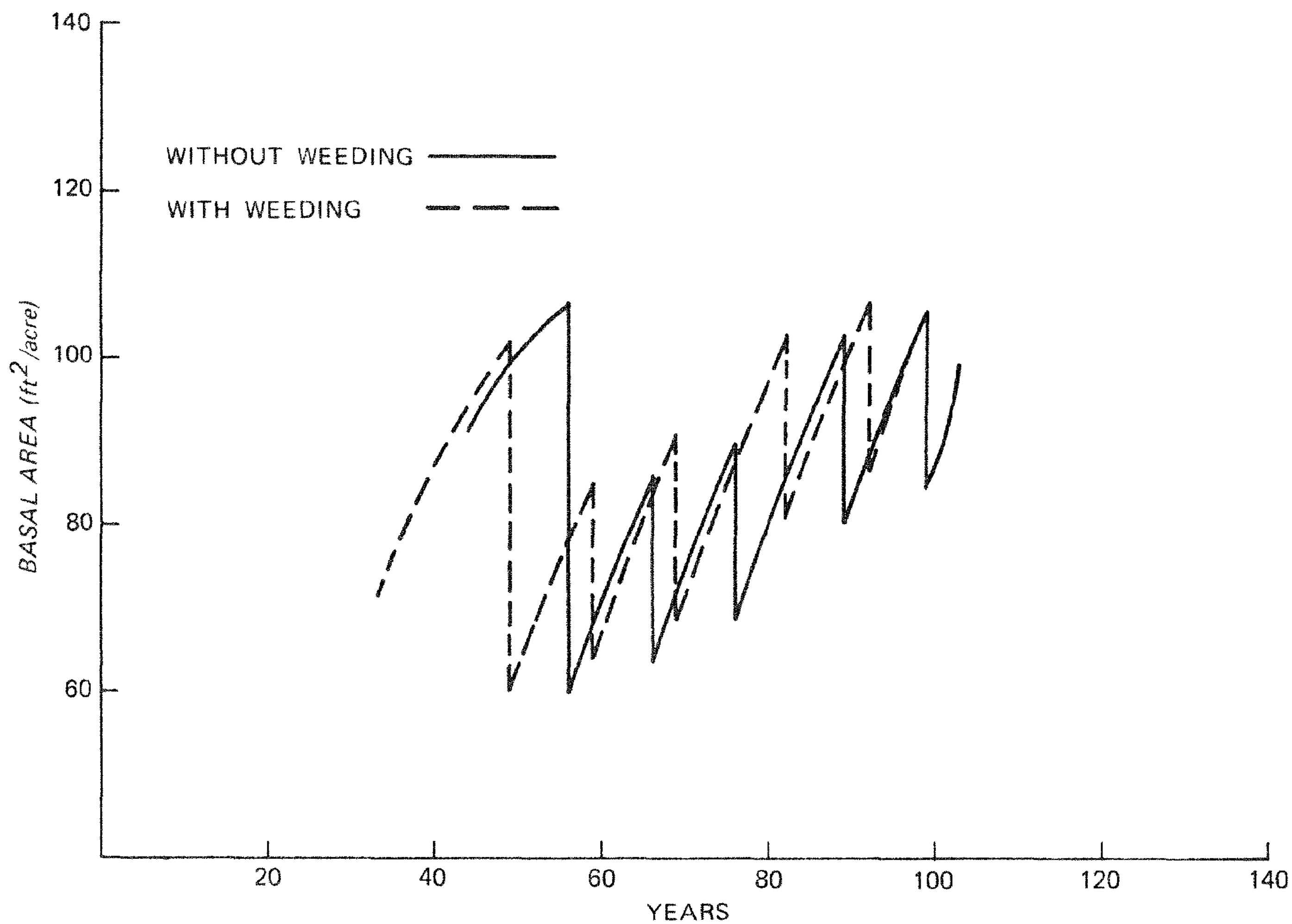

Figure 8.--Basal area response over time of 1/2 A-line thinning of weeded versus unweeded stands on site index 70.

Table 7.--Volumes removed in thinning and at harvest, by species and quality class, with and without removal of paper birch at first thinning after age 70 (Site index 70, A-line stocking, with weeding) (in cubic feet per acre)

Species	Quality class	Paper birch not removed			Paper birch removed		
		Thin 1	Thin 2	Harvest	Thin 1	Thin 2	Harvest
Beech	1	--	--	36	--	--	33
	2	--	--	54	--	--	47
	3	--	--	675	--	--	583
Yellow birch	1	--	--	1030	--	--	894
	2	--	--	562	--	--	489
	3	--	367	627	--	--	1039
Sugar maple	1	--	--	36	--	--	33
	2	--	--	167	--	--	145
	3	--	432	0	--	445	14
Red maple	1	--	--	149	--	--	130
	2	--	--	189	--	--	163
	3	--	445	--	--	445	--
Paper birch	1	--	--	--	--	208	--
	2	--	--	--	--	159	--
	3	258	130	--	258	130	--
White ash	1	--	--	54	--	--	47
	2	--	--	36	--	--	33
	3	16	--	--	16	--	--
Other	1	--	--	--	--	--	--
	2	--	--	--	--	--	--
	3	850	--	--	850	--	--
Total	1	0	0	1305	0	208	1137
	2	0	0	1008	0	159	877
	3	1124	1374	1302	1124	1020	1636

LITERATURE CITED

Blum, Barton M.
1966. Snow damage in young northern hardwoods and rapid recovery. J. For. 64:16-18.

Blum, Barton M., and Stanley M. Filip.
1962. A weeding in 10-year-old northern hardwoods--methods and time requirements. USDA For. Serv. Northeast. For. Exp. Stn. Res. Note 135, 7 p.

Gilbert, Adrian M.
1965. Stand differentiation ability in northern hardwoods. USDA For. Serv. Res. Pap. NE-37, 34 p.

Leak, William B.
1961. Development of second-growth hardwoods on Bartlett Experimental Forest--a 25-year record. USDA For. Serv. Northeast. For. Exp. Stn., Stn. Pap. 155, 8 p.

Leak, William B.
1969a. Sapling stand development: a compound exponential process. For. Sci. 16:177-180.

Leak, William B.
1969b. Stocking of northern hardwood regeneration based on exponential dropout rate. For. Chron. 45, (5):1-4.

Leak, William B., Dale S. Solomon, and Stanley M. Filip.
1969. A silvicultural guide for northern hardwoods in the Northeast. USDA For. Serv. Res. Pap. NE-143, 34 p., illus.

Marquis, David A.
1967. Clearcutting in northern hardwoods: results after 30 years. USDA For. Serv. Res. Pap. NE-85, 13 p.

Solomon, Dale S.
1974. Simulation of the development of natural and silviculturally treated stands of even-aged northern hardwoods. IUFRO Proc. 54:01-04, Growth models for tree and stand simulation. Swed. R. Coll. For. Res. Note 30, Stockholm.

Solomon, Dale S., and William B. Leak.
1969. Stocking, growth, and yield of birch stands. In Birch Symp. Proc. USDA For. Serv. Northeast. For. Exp. Stn. p. 106-118.

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