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# **OAKSIM:** An Individual-Tree Growth and Yield Simulator for Managed, Even-Aged, Upland Oak Stands

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## The Author

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## Abstract

OAKSIM is an individual-tree growth and yield simulator for managed, even-aged, upland oak stands. Growth and yield projections for various thinning alternatives can be made with OAKSIM for up to 50 years. Simulator components include an individual-tree diameter growth model, a mortality model, height prediction equations, bark ratio equations, a taper-based volume system, and a mathematical thinning rule based on actual data. The range of age, site, and stand conditions to which OAKSIM can be applied is discussed, and a numerical example is used to demonstrate computer output generated by the simulator.

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## Preface

This version of OAKSIM gives users a functional individual-tree growth and yield simulator for managed, even-aged, upland oak stands. A user's guide is in preparation. Improvements to OAKSIM will continue. A comprehensive statistical validation of growth and yield projections will be made when an improved mortality model and an ingrowth model are completed in the near future. A method of projecting individual-tree quality changes in relation to residual stocking after intermediate thinnings will also be incorporated into OAKSIM. Information on tree quality is essential input to an economics subroutine that will be added to determine optimum management alternatives in the upland oak timber type.

Users are encouraged to submit useful changes, extensions, or identified errors to the author for inclusion in the next version of OAKSIM. OAKSIM can become a valuable tool for forest managers only through close cooperation and coordination between researchers and users.

## NOTE:

The computer program described in this publication is available on request with the understanding that the U.S. Department of Agriculture cannot assure its accuracy, completeness, reliability, or suitability for any other purpose than that reported. The recipient may not assert any proprietary rights thereto nor represent it to anyone as other than a Government-produced computer program. For cost information write Donald E. Hilt, Northeastern Forest Experiment Station, USDA Forest Service, 359 Main Road, Delaware, OH 43015.

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## Introduction

Forest land managers need reliable growth and yield information to manage efficiently the nearly 109 million acres of upland oak timber type in the United States. This paper introduces the initial version of OAKSIM, an individual-tree growth and yield simulator for managed, even-aged, upland oak stands. OAKSIM is designed specifically to help land managers evaluate management alternatives. Although many cultural treatments must be considered for the management of upland oak stands, OAKSIM addresses that silvicultural treatment which has the most potential for influencing tree and stand growth and yield—intermediate thinning. The timing, intensity, and frequency of intermediate thinnings for a wide range of age, site, and stand conditions can be studied in detail with OAKSIM.

Growth and yield projections for up to 50 years after various thinning alternatives can be made with OAKSIM. Existing data bases do not support longer projections. Since OAKSIM is an individual-tree simulator, it provides valuable information on the species and size class of trees in the projected stand. This information is critical for determining the value of trees in the projected stand. Tree values are an essential ingredient for evaluating the economic aspects of thinning, especially in hardwood stands.

OAKSIM is written in FORTRAN and is flexible enough to accommodate a variety of user demands. Input and output program commands make OAKSIM easy to use while preserving the detail that is characteristic of individual-tree simulators. This paper deals primarily with the development and structure of the simulator; a forthcoming user's guide will provide easily understood operating instructions.

OAKSIM can be used to make growth and yield projections for a single stand or group of stands of particular interest, but a more logical approach may be to develop management guidelines by running the simulator for broader categories of age, site, and stand conditions. Management guidelines developed in this manner could be very useful, especially to forest land managers who do not have access to high-speed computers.

## Data

Data used to develop the individual-tree diameter growth and mortality models were collected on 77 permanent growth and yield plots in southern Ohio and southeastern Kentucky. Species composition ranged from nearly pure white oak on some Kentucky plots to a mixture of black and scarlet oaks on some Ohio plots.<sup>1</sup> Hickory

constituted a minor component of the overstory on some plots. Understory species consisted primarily of dogwood, red maple, yellow-poplar, sourwood, and serviceberry. The even-aged plots ranged from 29 to 93 years in age, and from 60 to 77 in site index according to Schnur's (1937) site index curves. Percent stocking after initial thinnings in 1962 ranged from 16 to 94 according to Gingrich's (1967) tree-area-ratio equation<sup>2</sup> (Fig. 1). Many plots have received a second or third thinning since 1962. The complete data set consists of remeasurements made periodically for 20 years on 9,455 trees that were larger than 2.5 inches d.b.h. after thinning in 1962.

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<sup>2</sup>Percent stocking (PS) contributed by the *i*th tree in the stand is calculated as follows:

$$PS_i = -.005066 + .016977 * DBH + .003168 * DBH * DBH.$$

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<sup>1</sup>See Little (1978) for scientific names of all species referred to in this paper.



Figure 1.—White oak plot in Kentucky, age 33. Stocking was reduced to 37 percent.

## Program Structure

The method used to thin the growth and yield plots is best described as "free thinning"—the marker was free to remove trees from all crown classes. The objective was to leave the specified stocking distributed on the best trees as evenly spaced as possible throughout the plot. In general, the larger cull and defective trees were cut first, then the competing trees of poor form and quality, then the intermediate and suppressed trees of lower quality and value. Finally, if necessary, lower value species and even some high-quality desirable species were removed from the main canopy to achieve a uniform spatial distribution. This is the most realistic, practical thinning method that can be applied at the present time by professional foresters in even-aged upland oak stands.

Developing all growth and yield components from one data base is most desirable. Unfortunately, this is seldom possible. A total of 2306 felled-tree and 2313 standing-tree heights were measured on unmanaged even-aged plots in six midwestern states to develop the height prediction equations. Bark-ratio equations were developed from data collected over the entire upland oak range. A total of 1619 trees, representing 10 species groups were sampled. The taper-based volume system was developed from measurements on 418 felled upland oak trees in five midwestern states. Since the height, bark, and volume equations were based on data collected from unmanaged stands, the effects of residual stocking on these components could not be assessed. This is not considered detrimental to OAKSIM's performance, however, because individual-tree diameter growth and mortality are by far the most important components affecting growth and yield projections in managed stands.

A generalized flow chart of the programming logic used in OAKSIM is shown in Figure 2. The control information specifies: (1) type of input data, (2) timing, intensity, and frequency of thinning, (3) tree volume calculations, and (4) type of output. If a stand table is provided in lieu of a tree list, OAKSIM generates a tree list as described later. A summary of initial stand conditions by species and size classes is then computed and printed (Table 1). The stand may be thinned initially or at any 5-year interval to a specified stocking level. A maximum of ten 5-year growth projections may be made. The 5-year intervals provide adequate resolution of growth and yield projections over time for most users. Linear interpolation may be used for estimates between the 5-year intervals.

Diameter growth of each residual tree is predicted for each 5-year period. The probability of mortality for each tree is then determined from this growth, the initial size of the tree, and the species of the tree. If the tree is classified as dead on the basis of this probability and a draw from a random number generator, it is removed from the list. If the net stand basal area growth is not within stand-level growth limitations, a modifier (described later) is applied to the diameter growth calculations and the 5-year growth cycle is repeated.

Inside-and outside-bark volumes to specified top diameters are calculated for individual trees from a predicted total tree height, the appropriate bark ratio equation, and a taper-based volume system. Stand and stock tables by species and size classes are printed after each 5-year interval for the initial stand, thinned trees, residual stand, mortality trees, and projected stand (Table 1). A stand-level summary is printed for each stand after all 5-year projections have been completed (Table 2). This summary is useful for comparing overall thinning strategies.

## Program Applications

OAKSIM can be applied to a wide range of stand, age, and site conditions. Like all simulators, however, OAKSIM has limitations, imposed primarily by the data bases used to construct the growth and yield models. Users must be cautious not to exceed these limitations because erroneous projections can occur. OAKSIM applications are limited to the following conditions:

- Even-aged upland oak stands only
- Oak component at least 75 percent of stand basal area
- Stand age 30 to 120 years
- Black oak site index 50 to 85
- Percent stocking 20 to 120 percent
- Tree d.b.h. 2.6 inches and larger
- Maximum 50-year projection

OAKSIM should be applied only to those stands composed primarily of oak species found on upland sites: white, black, scarlet, and chestnut. The simulator is not intended to be used on stands where northern red oak is the major oak component. It can, however, be used on stands where northern red oak is less than 15 percent of the stand basal area.

Stand structure should not differ radically from even-aged structures normally found on upland oak sites. Initial starting ages may range from 30 to 100 years. If the simulator is started at age 100, then projections should only be made for 20 years to the maximum 120 years. The simulator should not be started over. For example, if projections are made from ages 30 to 80, resulting output should not be used as input for a projection from ages 80 to 120. The program will terminate and error messages will be printed if a tree d.b.h. is less than 2.6 inches, or if stand age or site indexes fall outside their respective ranges of application. The user is responsible for meeting the other conditions.

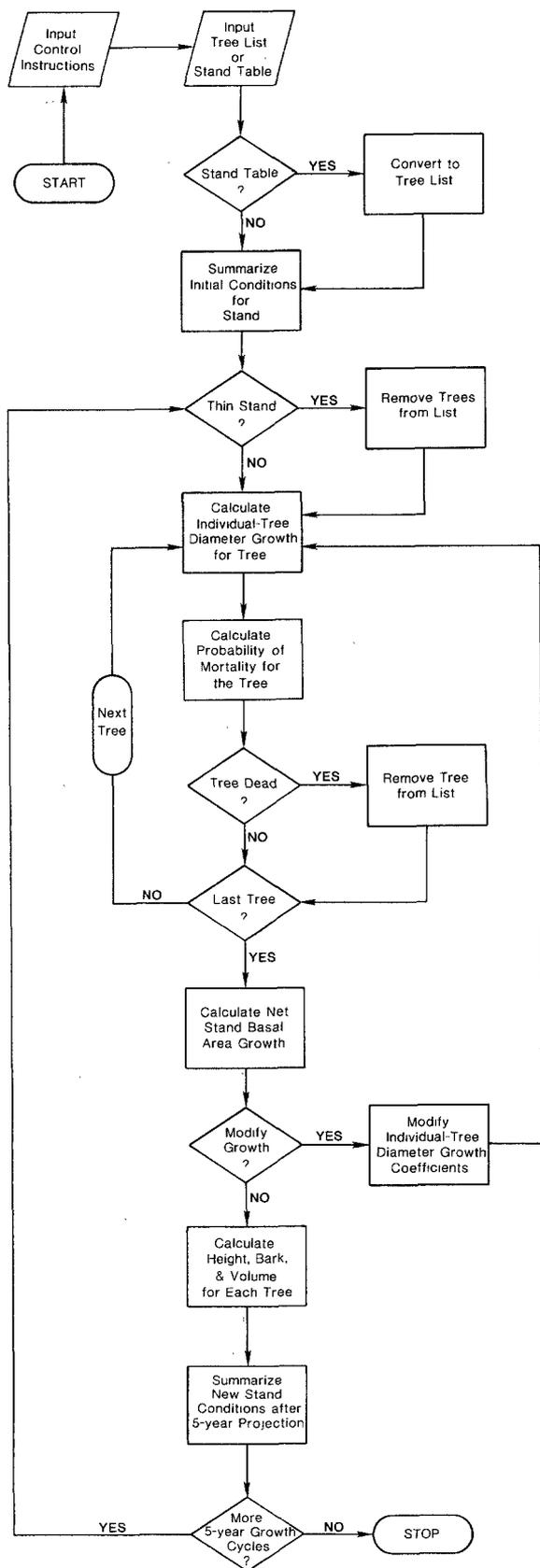


Figure 2.--Generalized flowchart of OAKSIM's operation.

### Program Input and Output

OAKSIM is designed to operate from a tree list containing the species and d.b.h. of each tree in the stand, but users may not always have access to a complete list of trees in a stand, except perhaps in research situations. A stand table input option, therefore, is included in OAKSIM to make the simulator more compatible with practical applications. Both the tree list and stand table options must be on a per-acre basis. The number of trees in each size and species (or species group) class must be specified with the stand table option. Size classes may be either 1- or 2-inch d.b.h. classes. A random number generator is called on to distribute the d.b.h.'s of trees in each species and d.b.h. class uniformly across the d.b.h. class. For example, if there are 25 white oak trees in the 6-inch d.b.h. class (a 1-inch class), the generated tree list will include 25 white oak trees uniformly distributed from 5.55 to 6.54 inches. Initial growth projections are then based on this generated tree list. This approach provides a close approximation to the actual distribution of trees across d.b.h. classes. The age and site index (for black oak) must also be entered for each stand.

OAKSIM's flexibility allows users to look at output for virtually any combination of species groups and product size classes. A maximum of five species groups may be specified by the user. Species identification codes in the tree-list or stand-table input will be assembled into groups according to user instructions. Product size classes may also be user-specified into three groups: sapling, pole, and sawtimber. Default values are 4.55 inches for poles and 11.55 inches for sawtimber.

(Text continued on page 11)

TABLE I

DATA TYPE AND STAND INFORMATION.

TYPE OF INPUT DATA: STAND TABLE  
 NUMBER OF STANDS: 1

STAND NUMBER	AGE	SITE INDEX
1	34.0	66.0

**1**

VOLUMES TO BE CALCULATED.

	TOP DIAMETERS	
	-----	-----
CUBIC VOLUME	4.0	0.0
BOARD FOOT VOLUME	8.0	6.0

MINIMUM LENGTH FOR CUBIC VOLUMES IS 4.0 FEET,  
 AND 8.0 FEET FOR BD FT VOLUMES.  
 PRODUCT SIZE CLASSES ARE 4.55 INCHES FOR POLES,  
 AND 8.55 INCHES FOR SAWLOGS.

**2**

HEIGHT AND BARK DATA.

SPECIES GROUP	HTGRP	RBAR	B0	B1
1	WO	0.910	0.881	0.056
2	BO	0.900	0.832	0.103
3	WO	0.930	0.919	0.045
4	WO	0.900	0.000	0.000

SPECIES CODES.

SPECIES GROUP	SPECIES CODES
1	1
2	2
3	3
4	ALL OTHER CODES ARE IN THIS GROUP.

PROJECTIONS.

NUMBER OF 5-YEAR PROJECTIONS: 10  
 1ST & LAST STAND-STOCK TABLES ALWAYS PRINTED.  
 ALL STAND TABLES PRINTED: YES  
 ALL STOCK TABLES PRINTED: NO

**5**

THINNING OPTIONS.

NUMBER OF THINNINGS: 1  
 THINNING METHOD: FREE THINNING  
 THINNING INTENSITIES BY SPECIES  
 GROUPS: 0 0 0 0

**6**

AGE THINNED	PERCENT STOCKING
34	40.0

TABLE I (continued)

**7**

SUMMARY STAND STATISTICS: INITIAL CONDITIONS FOR STAND AT AGE 34.

SPECIES :	1	2	3	4	5	TOTALS
<b>N TREES:</b>						
SAP	512.0	44.0	12.0	16.0		584.0
POLE	110.0	48.0	2.0	6.0		166.0
SAW	0.0	0.0	0.0	0.0		0.0
TOTAL	622.0	92.0	14.0	22.0		750.0
<b>BA:</b>						
SAP	34.1	3.0	0.8	1.2		39.1
POLE	17.6	8.7	0.3	0.9		27.5
SAW	0.0	0.0	0.0	0.0		0.0
TOTAL	51.7	11.6	1.2	2.1		66.6
<b>PS:</b>						
SAP	47.2	4.1	1.1	1.6		54.0
POLE	19.7	9.4	0.3	1.0		30.5
SAW	0.0	0.0	0.0	0.0		0.0
TOTAL	66.9	13.5	1.5	2.6		84.5
<b>AVG DBH:</b>						
SAP	3.4	3.5	3.5	3.6		3.5
POLE	5.4	5.7	5.3	5.3		5.5
SAW	0.0	0.0	0.0	0.0		0.0
<b>CVOB 4.0:</b>						
SAP	0.0	0.0	0.0	0.0		0.0
POLE	225.7	126.0	3.0	12.7		367.4
SAW	0.0	0.0	0.0	0.0		0.0
TOTAL	225.7	126.0	3.0	12.7		367.4
<b>CVIB 4.0:</b>						
SAP	0.0	0.0	0.0	0.0		0.0
POLE	196.7	108.2	2.8	10.3		317.9
SAW	0.0	0.0	0.0	0.0		0.0
TOTAL	196.7	108.2	2.8	10.3		317.9
<b>CVOB 0.0:</b>						
SAP	624.2	59.2	15.2	23.3		721.9
POLE	388.5	199.2	5.9	22.0		615.5
SAW	0.0	0.0	0.0	0.0		0.0
TOTAL	1012.7	258.3	21.1	45.3		1337.4
<b>CVIB 0.0:</b>						
SAP	537.1	49.7	13.9	18.9		619.6
POLE	333.8	167.1	5.4	17.8		524.0
SAW	0.0	0.0	0.0	0.0		0.0
TOTAL	870.9	216.8	19.3	36.7		1143.7
<b>BFVOL 8.0:</b>						
SAW	0.0	0.0	0.0	0.0		0.0
<b>BFVOL 6.0:</b>						
SAW	0.0	0.0	0.0	0.0		0.0

**8**

TABLE I (continued)

STAND TABLE: INITIAL CONDITIONS FOR STAND AT AGE 34.

DBH CLASS	SPECIES GROUPS					TOTALS
	1	2	3	4	5	
3	298.0	22.0	6.0	6.0	<b>9</b>	332.0
4	214.0	22.0	6.0	10.0		252.0
5	86.0	24.0	2.0	4.0		116.0
6	14.0	20.0	0.0	2.0		36.0
7	10.0	2.0	0.0	0.0		12.0
8	0.0	2.0	0.0	0.0		2.0
TOTALS	622.0	92.0	14.0	22.0		750.0

STAND TABLE: TREES REMOVED IN THINNING AT AGE 34.

DBH CLASS	SPECIES GROUPS					TOTALS
	1	2	3	4	5	
3	239.0	15.0	4.0	4.0	<b>10</b>	262.0
4	100.0	10.0	3.0	5.0		118.0
5	30.0	9.0	1.0	2.0		42.0
6	5.0	7.0	0.0	1.0		13.0
7	3.0	1.0	0.0	0.0		4.0
8	0.0	1.0	0.0	0.0		1.0
9	0.0	0.0	0.0	0.0		0.0
10	0.0	0.0	0.0	0.0		0.0
TOTALS	377.0	43.0	8.0	12.0		440.0

STAND TABLE: RESIDUAL STAND AFTER THINNING AT AGE 34.

DBH CLASS	SPECIES GROUPS					TOTALS
	1	2	3	4	5	
3	59.0	7.0	2.0	2.0	<b>11</b>	70.0
4	114.0	12.0	3.0	5.0		134.0
5	56.0	15.0	1.0	2.0		74.0
6	9.0	13.0	0.0	1.0		23.0
7	7.0	1.0	0.0	0.0		8.0
8	0.0	1.0	0.0	0.0		1.0
9	0.0	0.0	0.0	0.0		0.0
10	0.0	0.0	0.0	0.0		0.0
TOTALS	245.0	49.0	6.0	10.0		310.0

STAND TABLE: MORTALITY FOR GROWTH PERIOD BEGINNING AT AGE 34.

DBH CLASS	SPECIES GROUPS					TOTALS
	1	2	3	4	5	
3	3.0	1.0	0.0	0.0	<b>12</b>	4.0
4	1.0	0.0	0.0	0.0		1.0
5	1.0	0.0	0.0	0.0		1.0
6	0.0	0.0	0.0	0.0		0.0
7	0.0	0.0	0.0	0.0		0.0
8	0.0	0.0	0.0	0.0		0.0
9	0.0	0.0	0.0	0.0		0.0
10	0.0	0.0	0.0	0.0		0.0
TOTALS	5.0	1.0	0.0	0.0		6.0

STAND TABLE: INITIAL CONDITIONS FOR STAND AT AGE 39.

DBH CLASS	SPECIES GROUPS					TOTALS
	1	2	3	4	5	
3	27.0	3.0	1.0	0.0	<b>13</b>	31.0
4	81.0	11.0	3.0	2.0		97.0
5	72.0	7.0	1.0	5.0		85.0
6	44.0	12.0	1.0	2.0		59.0
7	7.0	10.0	0.0	1.0		18.0
8	4.0	4.0	0.0	0.0		8.0
9	5.0	0.0	0.0	0.0		5.0
10	0.0	1.0	0.0	0.0		1.0
TOTALS	240.0	48.0	6.0	10.0		304.0

STAND TABLE: INITIAL CONDITIONS FOR STAND AT AGE 84.

DBH CLASS	SPECIES GROUPS					TOTALS
	1	2	3	4	5	
5	1.0	0.0	0.0	0.0	<b>14</b>	1.0
6	9.0	1.0	2.0	0.0		12.0
7	20.0	2.0	1.0	0.0		23.0
8	41.0	1.0	0.0	2.0		44.0
9	43.0	6.0	0.0	1.0		50.0
10	22.0	6.0	1.0	1.0		30.0
11	13.0	3.0	0.0	1.0		17.0
12	5.0	5.0	1.0	0.0		11.0
13	2.0	6.0	0.0	0.0		8.0
14	4.0	1.0	0.0	0.0		5.0
15	1.0	0.0	0.0	0.0		1.0
16	3.0	0.0	0.0	0.0		3.0
17	0.0	1.0	0.0	0.0		1.0
TOTALS	164.0	32.0	5.0	5.0		206.0

TABLE I (continued)

SUMMARY STAND STATISTICS: INITIAL CONDITIONS FOR STAND AT AGE 84.

SPECIES :	1	2	3	4	5	TOTALS
<b>N TREES:</b>						
SAP	0.0	0.0	0.0	0.0		0.0
POLE	71.0	4.0	3.0	2.0		80.0
SAW	93.0	28.0	2.0	3.0		126.0
TOTAL	164.0	32.0	5.0	5.0		206.0
<b>BA:</b>						
SAP	0.0	0.0	0.0	0.0		0.0
POLE	21.7	1.1	0.7	0.7		24.2
SAW	55.2	19.9	1.3	1.7		78.1
TOTAL	76.9	21.0	2.0	2.4		102.3
<b>PS:</b>						
SAP	0.0	0.0	0.0	0.0		0.0
POLE	21.2	1.1	0.7	0.7		23.7
SAW	47.9	16.8	1.1	1.5		67.2
TOTAL	69.1	17.9	1.8	2.1		90.9
<b>AVG DBH:</b>						
SAP	0.0	0.0	0.0	0.0		0.0
POLE	7.5	7.1	6.4	8.1		7.4
SAW	10.3	11.3	11.0	10.1		10.5
<b>CVOB 4.0:</b>						
SAP	0.0	0.0	0.0	0.0		0.0
POLE	609.1	28.3	15.3	21.7		674.4
SAW	1978.3	676.0	48.4	60.0		2762.7
TOTAL	2587.4	704.3	63.6	81.8		3437.1
<b>CVIB 4.0:</b>						
SAP	0.0	0.0	0.0	0.0		0.0
POLE	525.5	24.0	14.0	17.6		581.1
SAW	1699.6	566.9	44.1	48.6		2359.2
TOTAL	2225.0	590.9	58.2	66.2		2940.3
<b>CVOB 0.0:</b>						
SAP	0.0	0.0	0.0	0.0		0.0
POLE	704.9	34.5	19.5	24.3		783.1
SAW	2071.2	702.8	50.0	63.1		2887.1
TOTAL	2776.0	737.3	69.5	87.4		3670.2
<b>CVIB 0.0:</b>						
SAP	0.0	0.0	0.0	0.0		0.0
POLE	604.3	28.8	17.8	19.7		670.6
SAW	1774.9	587.0	45.6	51.1		2458.6
TOTAL	2379.2	615.8	63.3	70.8		3129.2
<b>BFVOL 8.0:</b>						
SAW	3918.9	1721.8	145.3	88.5		5874.5
<b>BFVOL 6.0:</b>						
SAW	7263.7	2533.1	199.7	198.2		10194.7

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TABLE I (continued)

## SUMMARY STATISTICS FOR ENTIRE GROWTH PROJECTION:

16

ATTRIBUTE	STAND AGE											TOTALS
	34	39	44	49	54	59	64	69	74	79	84	
<b>N TREES:</b>												
INITIAL	750.0	304.0	290.0	281.0	269.0	261.0	250.0	240.0	227.0	216.0	206.0	-----
CUT	440.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0
RESIDUAL	310.0	304.0	290.0	281.0	269.0	261.0	250.0	240.0	227.0	216.0	216.0	-----
MORTALITY	6.0	14.0	9.0	12.0	8.0	11.0	10.0	13.0	11.0	10.0	10.0	104.0
<b>BA:</b>												
INITIAL	66.6	44.4	55.0	64.3	72.4	79.3	85.2	90.4	94.9	98.8	102.3	-----
CUT	33.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.8
RESIDUAL	32.8	44.4	55.0	64.3	72.4	79.3	85.2	90.4	94.9	98.8	98.8	-----
MORTALITY	0.4	1.0	1.0	1.8	1.3	2.1	2.5	2.6	3.2	3.4	3.4	19.2
NET GROWTH	11.6	10.6	9.3	8.1	6.9	6.0	5.2	4.5	3.9	3.5	3.5	69.5
GROSS GROWTH	12.0	11.6	10.3	9.9	8.2	8.0	7.7	7.1	7.1	6.9	6.9	88.7
<b>PS:</b>												
INITIAL	84.5	50.2	58.7	66.0	71.9	76.9	80.9	84.3	86.9	89.1	90.9	-----
CUT	44.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	44.5
RESIDUAL	40.0	50.2	58.7	66.0	71.9	76.9	80.9	84.3	86.9	89.1	89.1	-----
MORTALITY	0.5	1.3	1.2	2.1	1.4	2.2	2.5	2.8	3.1	3.2	3.2	20.4
NET GROWTH	10.2	8.5	7.3	5.9	5.1	4.0	3.3	2.6	2.2	1.9	1.9	50.9
GROSS GROWTH	10.7	9.9	8.5	8.0	6.5	6.2	5.9	5.4	5.3	5.1	5.1	71.4
<b>QUADRATIC DBH:</b>												
INITIAL	4.0	5.2	5.9	6.5	7.0	7.5	7.9	8.3	8.8	9.2	9.5	-----
CUT	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8
RESIDUAL	4.4	5.2	5.9	6.5	7.0	7.5	7.9	8.3	8.8	9.2	9.2	-----
MORTALITY	3.4	3.6	4.4	5.3	5.4	5.9	6.8	6.1	7.3	7.9	7.9	56.0
<b>CVOB 4.0:</b>												
INITIAL	367.4	506.2	969.8	1352.0	1699.4	2089.5	2327.8	2655.2	2990.9	3171.4	3437.1	-----
CUT	133.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	133.2
RESIDUAL	234.1	506.2	969.8	1352.0	1699.4	2089.5	2327.8	2655.2	2990.9	3171.4	3171.4	-----
MORTALITY	1.4	0.0	5.9	28.6	20.9	38.2	62.3	54.0	87.1	100.3	100.3	398.7
NET GROWTH	272.1	463.6	382.2	347.4	390.1	238.3	327.4	335.7	180.6	265.6	265.6	3202.9
GROSS GROWTH	273.5	463.6	388.1	375.9	411.0	276.5	389.7	389.7	267.7	365.9	365.9	3601.6
<b>CVIB 4.0:</b>												
INITIAL	317.9	436.8	835.2	1162.7	1460.5	1792.8	1996.5	2275.8	2561.2	2713.7	2940.3	-----
CUT	115.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	115.2
RESIDUAL	202.8	436.8	835.2	1162.7	1460.5	1792.8	1996.5	2275.8	2561.2	2713.7	2713.7	-----
MORTALITY	1.2	0.0	5.1	24.0	17.8	33.1	53.0	46.8	75.2	85.8	85.8	342.0
NET GROWTH	234.0	398.4	327.5	297.8	332.2	203.7	279.4	285.3	152.5	226.6	226.6	2737.5
GROSS GROWTH	235.3	398.4	332.6	321.8	350.1	236.8	332.4	332.1	227.7	312.4	312.4	3079.5
<b>CVOB 0.0:</b>												
INITIAL	1337.4	960.4	1409.2	1765.5	2077.6	2443.2	2652.8	2958.2	3266.1	3425.8	3670.2	-----
CUT	652.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	652.2
RESIDUAL	685.3	960.4	1409.2	1765.5	2077.6	2443.2	2652.8	2958.2	3266.1	3425.8	3425.8	-----
MORTALITY	8.2	18.0	21.2	49.1	34.6	56.1	77.1	75.0	102.6	113.8	113.8	555.6
NET GROWTH	275.1	448.8	356.3	312.1	365.5	209.7	305.4	307.8	159.7	244.4	244.4	2985.0
GROSS GROWTH	283.3	466.8	377.5	361.2	400.2	265.7	382.5	382.8	262.3	358.3	358.3	3540.6

TABLE 1 (continued)

ATTRIBUTE	STAND AGE										TOTALS	
	34	39	44	49	54	59	64	69	74	79		84
<b>CVIB 0.0:</b>												
INITIAL	1143.7	819.5	1202.4	1506.3	1773.2	2084.1	2263.0	2523.7	2785.3	2920.3	3129.2	558.2
CUT	558.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	473.1
RESIDUAL	585.4	819.5	1202.4	1506.3	1773.2	2084.1	2263.0	2523.7	2785.3	2920.3	3129.2	2543.8
MORTALITY	7.0	15.3	18.1	41.2	29.2	48.1	65.1	64.3	88.0	96.8	305.7	3016.9
NET GROWTH	234.0	382.9	303.9	266.9	310.9	178.9	260.7	261.6	135.1	208.9	305.7	5874.5
GROSS GROWTH	241.1	398.3	322.0	308.0	340.1	227.0	325.8	325.9	223.0	305.7	305.7	5996.5
<b>BFVOL 8.0:</b>												
INITIAL	0.0	0.0	140.3	385.6	812.3	1367.2	1688.7	2830.8	3908.1	4676.7	5874.5	0.0
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RESIDUAL	0.0	0.0	140.3	385.6	812.3	1367.2	1688.7	2830.8	3908.1	4676.7	5874.5	122.0
MORTALITY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.5	90.5	1197.7	5874.5
NET GROWTH	0.0	140.3	245.3	426.7	554.9	321.5	1142.2	1077.2	768.7	1197.7	1288.2	5996.5
GROSS GROWTH	0.0	140.3	245.3	426.7	554.9	321.5	1142.2	1077.2	800.2	1288.2	1288.2	5996.5
<b>BFVOL 6.0:</b>												
INITIAL	0.0	0.0	546.6	1080.2	1866.5	3198.8	3982.0	5509.3	7287.8	8692.5	10194.7	0.0
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RESIDUAL	0.0	0.0	546.6	1080.2	1866.5	3198.8	3982.0	5509.3	7287.8	8692.5	10194.7	295.7
MORTALITY	0.0	0.0	0.0	36.2	0.0	0.0	40.0	0.0	65.5	154.0	1502.2	10194.7
NET GROWTH	0.0	546.6	533.5	786.3	1332.3	783.2	1527.2	1778.6	1404.7	1502.2	1656.2	10490.3
GROSS GROWTH	0.0	546.6	533.5	822.5	1332.3	783.2	1567.2	1778.6	1470.1	1656.2	1656.2	10490.3

TABLE 2 SUMMARY STATISTICS FOR ENTIRE GROWTH PROJECTION:

ATTRIBUTE	STAND AGE										TOTALS	
	34	39	44	49	54	59	64	69	74	79		84
<b>N TREES:</b>												
INITIAL	750.0	653.0	572.0	508.0	457.0	419.0	384.0	354.0	328.0	301.0	281.0	0.0
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RESIDUAL	750.0	653.0	572.0	508.0	457.0	419.0	384.0	354.0	328.0	301.0	281.0	469.0
MORTALITY	97.0	81.0	64.0	51.0	38.0	35.0	30.0	26.0	27.0	20.0	20.0	469.0
<b>BA:</b>												
INITIAL	66.6	75.8	83.2	89.2	94.2	98.4	102.0	105.0	107.8	110.2	112.3	0.0
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RESIDUAL	66.6	75.8	83.2	89.2	94.2	98.4	102.0	105.0	107.8	110.2	112.3	58.9
MORTALITY	5.8	6.7	6.2	5.9	5.8	6.0	5.4	5.4	6.3	5.5	5.5	45.7
NET GROWTH	9.2	7.4	6.0	5.0	4.2	3.6	3.1	2.7	2.4	2.2	2.2	104.7
GROSS GROWTH	15.0	14.1	12.2	10.8	10.0	9.6	8.5	8.2	8.7	7.6	7.6	104.7
<b>PS:</b>												
INITIAL	84.5	90.3	94.1	96.8	98.8	100.5	101.7	102.5	103.2	103.4	103.8	0.0
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RESIDUAL	84.5	90.3	94.1	96.8	98.8	100.5	101.7	102.5	103.2	103.4	103.8	68.3
MORTALITY	8.2	8.7	7.8	7.0	6.5	6.6	5.9	5.7	6.5	5.4	5.4	19.3
NET GROWTH	5.7	3.8	2.7	2.0	1.7	1.1	0.9	0.6	0.2	0.4	0.4	87.6
GROSS GROWTH	13.9	12.5	10.5	9.1	8.2	7.7	6.7	6.4	6.7	5.8	5.8	87.6

TABLE 2 (continued)

ATTRIBUTE	STAND AGE											TOTALS
	34	39	44	49	54	59	64	69	74	79	84	
<b>QUADRATIC DBH:</b>												
INITIAL	4.0	4.6	5.2	5.7	6.1	6.6	7.0	7.4	7.8	8.2	8.6	-----
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
RESIDUAL	4.0	4.6	5.2	5.7	6.1	6.6	7.0	7.4	7.8	8.2		-----
MORTALITY	3.3	3.9	4.2	4.6	5.3	5.6	5.7	6.2	6.6	7.1		52.5
<b>CVOB 4.0:</b>												
INITIAL	367.4	722.7	1094.1	1458.8	1903.1	2144.6	2453.1	2797.0	3040.7	3308.2	3487.3	-----
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
RESIDUAL	367.4	722.7	1094.1	1458.8	1903.1	2144.6	2453.1	2797.0	3040.7	3308.2		-----
MORTALITY	7.5	24.4	34.5	47.1	87.3	106.9	88.8	107.9	137.9	135.6		778.0
NET GROWTH	355.4	371.4	364.7	444.3	241.5	308.5	343.9	243.6	267.6	179.1		3120.0
GROSS GROWTH	362.8	395.8	399.2	491.4	328.8	415.4	432.8	351.5	405.5	314.7		3897.9
<b>CVIB 4.0:</b>												
INITIAL	317.9	625.2	945.2	1258.5	1638.3	1845.3	2108.7	2401.3	2609.1	2836.9	2990.0	-----
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
RESIDUAL	317.9	625.2	945.2	1258.5	1638.3	1845.3	2108.7	2401.3	2609.1	2836.9		-----
MORTALITY	6.4	21.1	29.8	40.7	75.2	92.0	76.5	92.7	117.7	116.2		668.4
NET GROWTH	307.2	320.0	313.3	379.8	207.0	263.4	292.6	207.9	227.8	153.1		2672.1
GROSS GROWTH	313.7	341.1	343.1	420.5	282.2	355.4	369.1	300.6	345.5	269.3		3340.4
<b>CVOB 0.0:</b>												
INITIAL	1337.4	1674.0	2001.4	2271.7	2617.9	2779.3	3017.3	3294.4	3484.5	3699.2	3838.0	-----
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
RESIDUAL	1337.4	1674.0	2001.4	2271.7	2617.9	2779.3	3017.3	3294.4	3484.5	3699.2		-----
MORTALITY	107.6	137.0	137.0	134.9	152.8	166.8	140.9	150.2	181.5	165.7		1474.3
NET GROWTH	336.6	327.3	270.3	346.3	161.4	237.9	277.1	190.1	214.7	138.8		2500.6
GROSS GROWTH	444.2	464.3	407.3	481.2	314.2	404.7	418.0	340.3	396.3	304.4		3974.9
<b>CVIB 0.0:</b>												
INITIAL	1143.7	1431.2	1710.3	1940.8	2234.6	2372.4	2575.6	2811.2	2973.9	3157.2	3276.5	-----
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
RESIDUAL	1143.7	1431.2	1710.3	1940.8	2234.6	2372.4	2575.6	2811.2	2973.9	3157.2		-----
MORTALITY	92.1	116.9	117.0	115.5	130.3	141.8	119.9	127.9	153.8	141.0		1256.3
NET GROWTH	287.5	279.1	230.5	293.8	137.8	203.1	235.7	162.7	183.3	119.3		2132.9
GROSS GROWTH	379.6	396.0	347.4	409.3	268.1	345.0	355.6	290.6	337.1	260.3		3389.1
<b>BFVOL 8.0:</b>												
INITIAL	0.0	0.0	0.0	54.8	510.7	517.1	1028.6	1451.9	2015.4	2883.0	3579.3	-----
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
RESIDUAL	0.0	0.0	0.0	54.8	510.7	517.1	1028.6	1451.9	2015.4	2883.0		-----
MORTALITY	0.0	0.0	0.0	0.0	56.8	26.6	0.0	0.0	27.9	28.3		139.6
NET GROWTH	0.0	0.0	54.8	455.9	6.4	511.5	423.3	563.5	867.6	696.2		3579.3
GROSS GROWTH	0.0	0.0	54.8	455.9	63.3	538.1	423.3	563.5	895.5	724.5		3718.9
<b>BFVOL 6.0:</b>												
INITIAL	0.0	0.0	285.6	633.6	1355.3	1599.7	2307.2	3570.2	4745.8	6373.9	7739.3	-----
CUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
RESIDUAL	0.0	0.0	285.6	633.6	1355.3	1599.7	2307.2	3570.2	4745.8	6373.9		-----
MORTALITY	0.0	0.0	0.0	0.0	80.1	58.6	0.0	0.0	104.2	149.9		392.7
NET GROWTH	0.0	285.6	348.0	721.7	244.3	707.5	1263.0	1175.5	1628.1	1365.4		7739.3
GROSS GROWTH	0.0	285.6	348.0	721.7	324.4	766.1	1263.0	1175.5	1732.3	1515.2		8131.9

OAKSIM also allows considerable flexibility in calculating tree volumes. Merchantability standards may be specified. Two top d.i.b.'s for cubic volume and two top d.i.b.'s for board-foot volume calculations are specified by the user. Minimum lengths for both cubic and board-foot volumes may also be specified. Default values are 4.0 and 8.0 feet, respectively. The appropriate height prediction equation (either white or black oak) and bark ratio equations for each species group are assigned by the user.

The thinning option is initiated by user input. A list of the stand ages (initially or at any 5-year interval) and the desired percent stockings after thinning is all that is required.

Program output is also controlled by user input. Stand and stock tables for initial and final conditions are always printed (Table 1). The user may, however, elect to have all intermediate stand tables, stock tables, or both printed. The final summary table is always printed.

### Growth Components

#### Diameter Growth

A distance-independent, individual-tree diameter growth model (Hilt 1983) is used in OAKSIM. The random variation of the model is used to allow trees within a given stand to change position over time. The mean 5-year basal area growth (BAG5YR) of an individual tree is predicted with the following equation:

$$\text{BAG5YR} = \text{BETA} * \text{DBH} ** 2 \quad (1)$$

where BETA = (6.96762087

$$* 10 ** (-6)) * (\text{SI} ** 1.5731724)$$

$$* \text{EXP}(-.11839854 * \text{DBAR} - .01198244 * \text{PS}) \quad (2)$$

SI is the site index, DBAR is the quadratic mean stand diameter, PS is the percent stocking of the stand, and EXP is the base of the natural logarithms. All calculations in OAKSIM are made with double precision arithmetic.

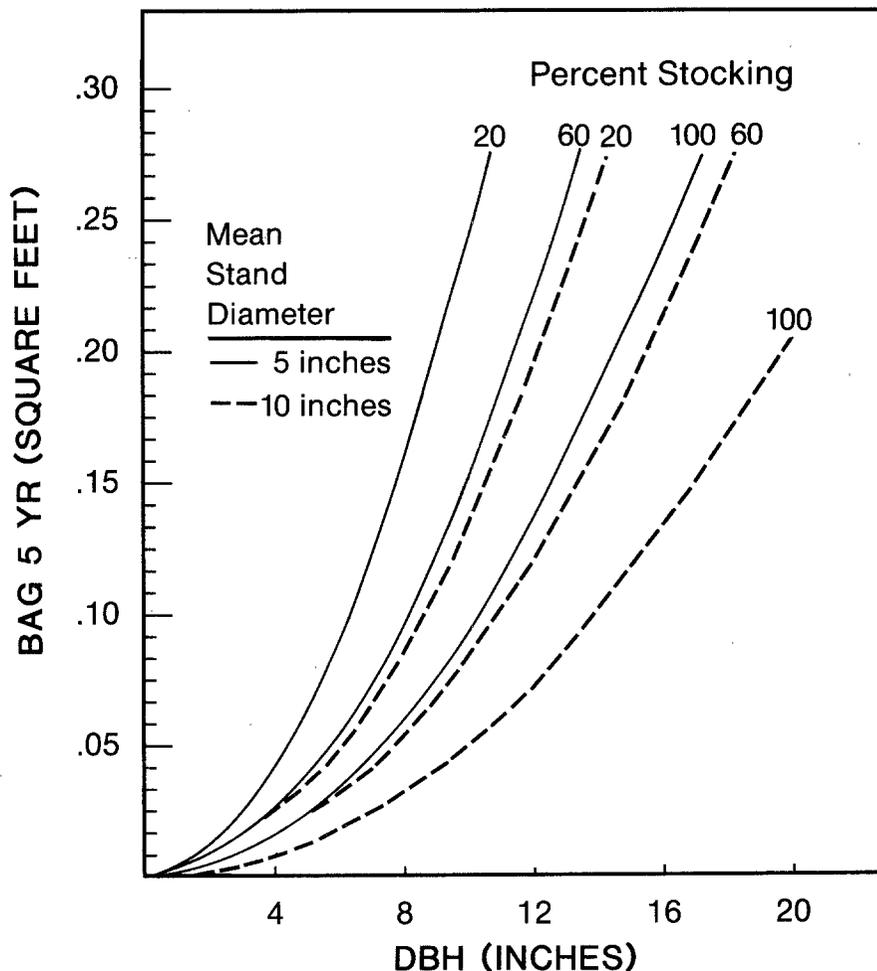


Figure 3.--Predicted 5-year basal-area growth rates (BAG5YR) for site index 70.

Equations (1) and (2) are used to predict growth for all tree species in a stand. The tree size variable, DBH, also accounts for growth differences among species. In other words, big trees grow faster—regardless of species. Trees in the black oak group (black, scarlet, and northern red) usually are larger, and therefore grow faster, than white and chestnut oaks in the same stand. The equations are applicable, however, only in stands where tree size differentiation has already occurred—stands at least 30 years old. Growth rates for other species that normally associate with upland oaks, such as dogwood, red maple,

and yellow-poplar, can also be safely predicted with these equations as long as they are not the major component of the stand (see Program Applications). Bigtooth aspen, an unusually fast grower, would probably be slightly underestimated. Predicted growth rates for a range of stocking and mean stand diameter conditions are shown in Figure 3 for site index 70.

The standard deviation (SIGMA) of the mean 5-year basal area growth for a given tree is calculated as follows:

$$\text{SIGMA} = 0.00915129 * \text{EXP}(0.12639572 * \text{DBH}) \quad (3)$$

A random number generator is then used to generate a random number (Z) from a normal distribution with mean = 0 and variance = 1. The random growth rate (X) about the mean growth (BAG5YR) for a given tree is then calculated as:

$$X = Z * \text{SIGMA} + \text{BAG5YR} \quad (4)$$

The random 5-year basal area growth rate is then converted with appropriate arithmetic to 5-year diameter growth.

Equations 1 through 4 are used to predict diameter growth rates for the first 5-year projection. Diameter growth rates for successive 5-year projections are made with a random number draw from a conditional mean growth and a conditional standard deviation based on the bivariate normal distribution (see Hilt 1983). The conditional equations are based on values from equations 1 through 4 for both the 5-year period of interest and the previous 5-year period. Use of the bivariate normal approach guarantees that fast-growing trees have a higher probability of remaining fast growers, and slow growers will remain slow growers.

#### Mortality

The probability of mortality (PMORT) for an individual tree is determined at the beginning of each 5-year projection with the following logistic function:

$$\text{PMORT} = 1.0 / (1.0 + \text{EXP}(B_0 + B_1 * \text{DBH} + B_2 * \text{DGROW})) \quad (5)$$

where DGROW is the periodic annual diameter growth of the tree for the past 5 years. Variations in mortality due to site, age, and stocking for a given size tree are accounted for with the DGROW variable. If PMORT is calculated to be less than 0.001, then PMORT is

assigned the value 0.001. This assignment of a small probability of mortality accounts for fast growing and very large trees that die occasionally at random times for no apparent reason. Predicted, rather than past, diameter growth rates are used for DGROW during the initial 5-year projection because past growth is hardly ever known initially. A random number between 0 and 1, drawn from a uniform distribution, is used to decide whether the tree dies. If the random number is less than PMORT, the tree is considered dead and removed from the list.

Only one diameter growth equation is required for all species, but several are required for mortality. For example, oak trees in the black oak group usually have a higher probability of mortality for a given d.b.h. than oak trees in the white oak group. Equation (5), therefore, was fitted to data from four species groups: (1) white oak, (2) black oak, (3) other trees (primarily hickory), and (4) understory species such as dogwood and sourwood. Coefficients in equation (5) for each group are listed in Table 3. PMORT is plotted over DGROW by DBH classes for the white oak group in Figure 4.

**Table 3.—Coefficients for mortality model (equation 5):**  
**PMORT = 1.0/(1.0+EXP(B0+B1\*DBH+B2\*DGROW))**

Species Group	B0	B1	B2
White oak <sup>a</sup>	-1.99	0.356	66.58
Black oak <sup>b</sup>	-2.48	.312	34.83
Other trees <sup>c</sup>	-.183	.246	57.35
Understory <sup>d</sup>	.341	.132	29.59

<sup>a</sup>White and chestnut oaks

<sup>b</sup>Black, scarlet, and northern red oaks

<sup>c</sup>Hickory, red maple, yellow poplar

<sup>d</sup>Dogwood, sourwood, sassafras, serviceberry, shrubs

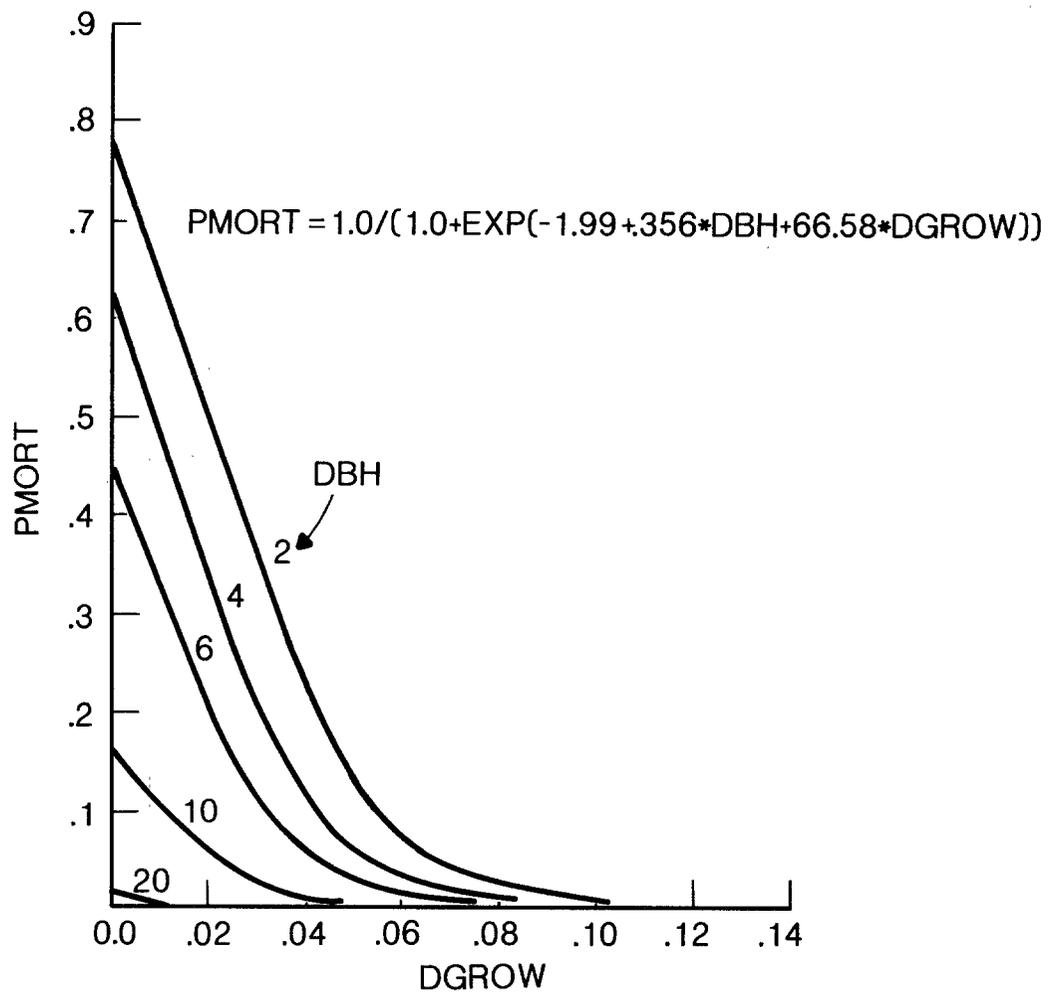


Figure 4.—Individual-tree probability of mortality (PMORT) for white oak group. DGROW is periodic annual diameter growth.

## Calibration

### Background

Calibration is the act of adjusting the simulator to meet actual growth and yield situations. Theoretically, all one must do is combine the diameter growth and mortality equations 1 through 5, and the simulator will function for all age, site, and stand conditions. Unfortunately, this is seldom the case. Nearly all major simulators designed to handle a wide range of applications have required some modification. Modification is necessary with individual-tree simulators because the probability of mortality is dependent on growth, and growth in turn is dependent on the stocking after dead trees have been removed. Sometimes slight modelling errors become cumulative and cause longer projections to go astray. Modification is also necessary because not all variations in a growth and yield projection are completely accounted for by the growth models.

OAKSIM was calibrated by comparing growth and yield projections with four sources of information: (1) actual growth and yield data from the managed stands discussed in the Data section, (2) upland oak yield tables for unmanaged stands prepared by Schnur (1937), (3) stand level projections made with GROAK (Dale 1972), and (4) personal experience. Although statistical validation tests have not yet been made, numerous comparisons with the 20-year managed stand data were performed. Longer projections of 50 years for unmanaged stands were compared with Schnur's tables up to age 80. Very few stands over age 80 were included in Schnur's tables for the simple reason that they did not exist in 1937. GROAK, a stand-level growth and yield model developed from the same managed stands used for OAKSIM, provided excellent comparisons for overall stand growth to age 100. Personal experience provides the added element of "feel" for whether the projections are realistic.

There are basically five components that need careful consideration for the calibration of an individual-tree simulator: (1) stand basal area growth (net and gross), (2) number of trees (live and dead), (3) minimum and maximum diameters of trees in the projected stand, (4) distribution of trees over d.b.h., and (5) relative proportions of trees by species groups. Most other stand components, such as mean stand diameter and percent stocking, will follow accordingly if these five components are correct. Volume, which also should follow accordingly, was not considered during the calibration of OAKSIM because tree volumes, as discussed later, are assigned to trees after the projection has been made.

### Modifiers

Net periodic annual basal area growth (BAG) for a given stand is first predicted with the following equation from GROAK;

$$\text{BAG} = \text{BA} * \text{AGE}^{**(-.8)} * \text{LOG}(\text{BA}) + .68521 * \text{BA} * \text{AGE}^{**(-.75)} + .011383 * \text{BA} * \text{SI} * \text{AGE}^{**(-1.05)} \quad (6)$$

where BA is the stand basal area, and AGE is the stand age. This equation is incremented five times to arrive at the net 5-year basal area growth for the stand. Individual-tree basal area growth rates from (4) are then multiplied by a constant, k, until the net stand basal area growth is within 2 percent of the growth predicted with GROAK. The value of k must be determined iteratively because net growth is the difference between gross growth for the 5-year period (growth of all survivor trees; Husch et al. 1972) and trees removed from the list with the mortality model. Many simulators use stand-level modifiers to adjust individual-tree growth rates, and GROAK is a wise choice for upland oaks because it has been extensively and successfully applied

over a wide geographic area of the upland oak timber type.

After stand growth was calibrated, the total number of trees per acre and the relative number of trees in each species group required some adjustment, particularly over site index. This adjustment is made with a reassignment of PMORT from equation (5):

$$\text{PMORT} = \text{PMORT} * 0.8 \quad (7)$$

for the black oak group, and

$$\text{PMORT} = \text{PMORT} * (0.5 + 0.025 * \text{SI}) \quad (8)$$

for all other species groups. Equation (7) simply lowers the probability of mortality for black oak for all conditions, and equation (8) increases the probability of mortality with increasing values of site index for the other species groups. The probability of mortality for a black oak tree of a given d.b.h. still remains higher than other species for most circumstances.

Minimum and maximum diameters, and also the distribution of trees in the projected stand, are adjusted with the reassignment of SIGMA from equation (3):

$$\text{SIGMA} = \text{SIGMA} * (1.88945 - .07837 * \text{SI} + .00087 * \text{SI}^{**2}) \quad (9)$$

Variation in tree growth for a given d.b.h. was found to increase with increasing site index. Equations (1) through (5) and the appropriate modifiers in equations (6) to (9) expand OAKSIM's application to a wider range of site index conditions than those available in the 20-year managed stand data base.

## Volume Computation

### Tree Height

Individual-tree volumes in OAKSIM are based on four components: (1) tree d.b.h. and species (available from the projected tree list), (2) height equations, (3) taper equations, and (4) bark ratio equations. Total tree heights (HT) are assigned to individual trees at each 5-year interval with equations developed for upland oaks by Hilt and Dale (1982):

$$HT = 4.5 + B0 * (1.0 - \text{EXP}(B1 * \text{DBH})) \quad (10)$$

where model coefficients B0 and B1 are based on stand age and site index. Height prediction equations are available only for trees in the white and black oak groups. Until height prediction equations for other species groups can be developed, either the white or black oak equation must be used. Errors that arise from this circumstance are not considered major because the tree size variable, DBH, again accounts for a considerable portion of the species effect. Equations for the black oak group for site index 60 are shown in Figure 5.

### Taper Equations

Diameters inside bark (DIB) up the stem are calculated for individual trees with the taper equation developed by Hilt (1980):

$$\begin{aligned} (\text{DIB}/\text{DOB})^{**2} = & X^{**1.5} \\ & +.003040(X^{**1.5}-X^{**3})*\text{HT} \\ & +.000226(X^{**1.5}-X^{**3})*\text{DBH}*\text{HT} \\ & +.003210(X^{**1.5}-X^{**30})*\text{DBH} \\ & -.000212(X^{**1.5}-X^{**30})*\text{DBH}*\text{HT} \end{aligned} \quad (11)$$

where  $X = (\text{HT}-h)/(\text{HT}-4.5)$ , and  $h$  = height at measurement point (feet). The same taper equation is used for all species. Trees must be at least 2.6 inches in d.b.h. Sample tree profiles generated with (11) are shown in Figure 6.

### Bark Ratio

The ratio of DIB to DOB up the stem is estimated for each tree with the equation developed by Hilt et al. (1983):

$$\text{DIB}/\text{DOB} = B0 + B1 * (\text{DOB}/\text{DBH}) \quad (12)$$

Values of the model coefficients, B0 and B1, for 10 species groups are listed in Table 4. The DIB/DOB ratio either remains constant or decreases up the stem for all 10 groups. If a mean DIB/DOB ratio at breast height (RBAR) is available, then B0 is set equal to the quantity  $(\text{RBAR}-B1)$  to adjust the ratios to local conditions. Equation (12) is plotted in Figure 7 for white oak, chestnut oak, and black cherry.

**Table 4.--Coefficients for bark ratio model (equation 12):**

Species	B0	B1
White oak	0.881	0.056
Chestnut oak	.774	.149
Black oak	.832	.103
Northern red oak	.864	.084
Southern red oak	.888	.040
Black cherry	.934	.017
Yellow-poplar	.840	.087
Red maple	.919	.045
Sugar maple	.873	.017
American beech	.931	.025

### Program Execution for Volume

Appropriate tree height and bark ratio equations are assigned to each species group by the user. Total height is then assigned to a tree based on the projected d.b.h., the age and site index of the stand, and the species group to which the tree belongs. Heights ( $h$ ) to user-specified top d.i.b.'s are then calculated with a bisection algorithm.

Minimum merchantable lengths specified by the user must be met, or no volumes will be calculated. Default values are 4.0 feet for cubic volume and 8.0 feet for board-foot volumes. The merchantable portion of the stem is then divided into 50 equal segments, and the d.i.b. and d.o.b. at each section point are calculated with (11) and (12). Cubic volumes of each section are calculated as truncated cones and summed to obtain volumes inside and outside bark for the tree. A 1-foot cylindrical stump is also included in cubic volume values. Board-foot volumes are calculated from 16-foot logs with the International 1/4-inch rule. Fractions of logs are included if they are not exactly 16 feet.

### Thinning Rule

The thinning rule used in OAKSIM is based on a mathematical model derived from the actual thinned plots discussed in the Data section. Complete development of the model will be documented in a forthcoming publication. The model has the following form:

$$\begin{aligned} \text{CUTFRQ}(I) = & 1.0 \\ & -\text{EXP}(-1.77980 * \text{CUMFRQ}(I) \\ & +.019849 * \text{CUMFRQ}(I) * \text{THINPS}) \end{aligned} \quad (13)$$

where CUTFRQ (I) is the cumulative frequency of the trees to be cut in the  $i$ th d.b.h. class divided by the total number of live trees in the stand, CUMFRQ (I) is the cumulative relative frequency of the live trees in the  $i$ th d.b.h. class, and THINPS is the percent stocking desired after thinning. For example, if a thinning to the 40 percent residual stocking level were desired in a stand with 500 total stems and 100 stems in the 3-inch d.b.h. class, CUMFRQ (3) would equal 0.20, CUTFRQ (3) would equal 0.18, and the resulting number of

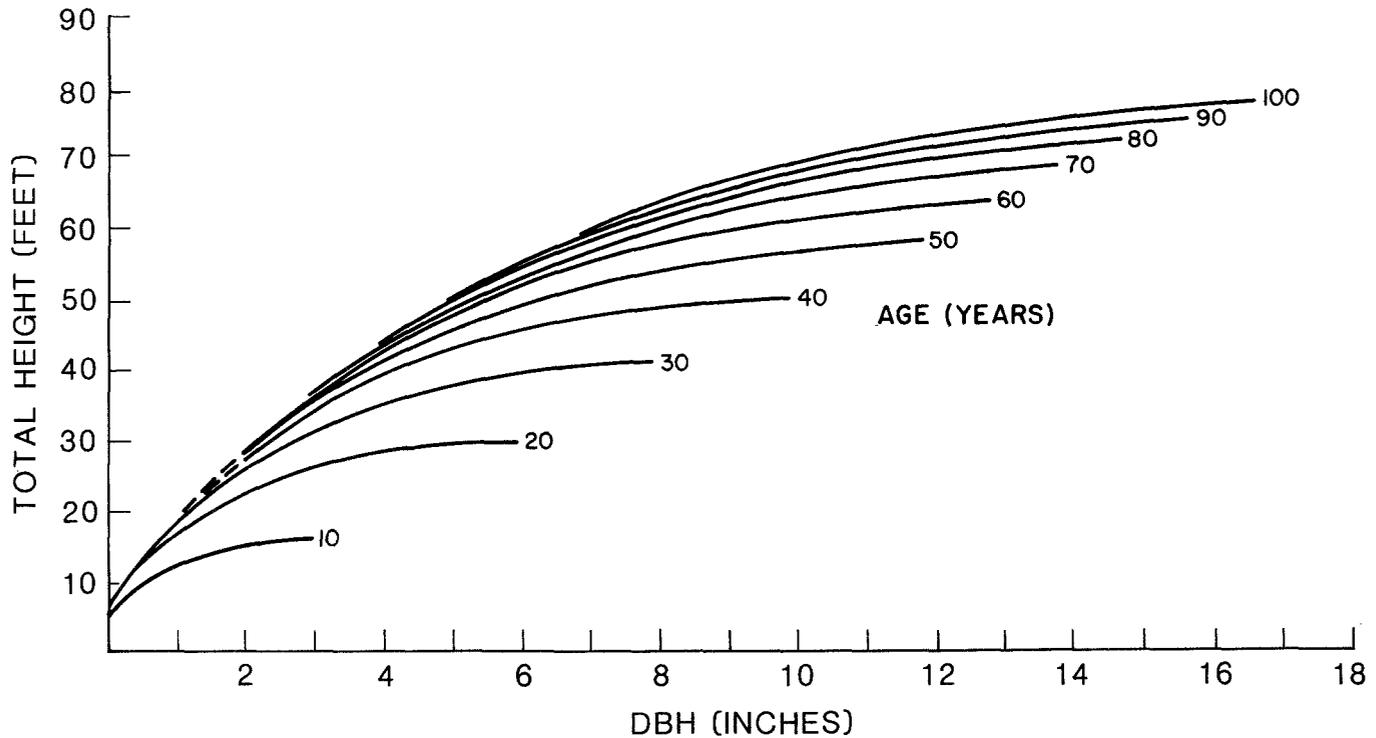


Figure 5.—Height-diameter-age curves for black oak, site index 60.

trees to be removed in the 3-inch class would be equal to  $0.18 \times 500 = 89$ . Age and site index did not have a significant effect on the thinning rule. Equation (13) is plotted in Figure 8 for a range of THINPS values.

The thinning rule makes every attempt to duplicate the actual thinning method applied by professional foresters in managed upland oak stands. OAKSIM is one of the few simulators that uses a thinning rule based on actual data, not artificial rules governed only by computer programming. Until additional plots can be established to study other thinning methods in upland oak stands, such as thinning strictly from above or below, this thinning rule should be used because the growth models are based on this

thinning method. There is, however, some flexibility with OAKSIM. Three options are available for distributing cut trees across species groups within a d.b.h. class: (1) maintain the same proportion of species as the unthinned stand, (2) double the allocated cut for specified species groups, and (3) eliminate specified species groups entirely. Only minor species groups such as understory species should be eliminated with the third option. Major species groups such as white oak or black oak should not be eliminated.

OAKSIM uses an iterative application of the thinning rule to insure that all d.b.h. and species groups are thinned accordingly. Two or three passes through the

tree list are generally required to reduce the stand to the desired THINPS.

#### Random Number Generator

A random number generator is used in OAKSIM to convert stand tables to tree lists and to calculate individual-tree diameter growth rates and probabilities of mortality. A random number (U) is drawn from a uniform distribution between 0 and 1. This number is used unaltered to construct tree lists and calculate the probability of mortality, but is converted to a normal deviate (XNORM) from a distribution with mean = 0 and variance = 1 with the following equation for diameter growth calculations:

$$XNORM = \text{SQRT}(-2.0 \cdot \text{LOG}(U1)) \cdot \text{COS}(6.283 \cdot U2) \quad (14)$$

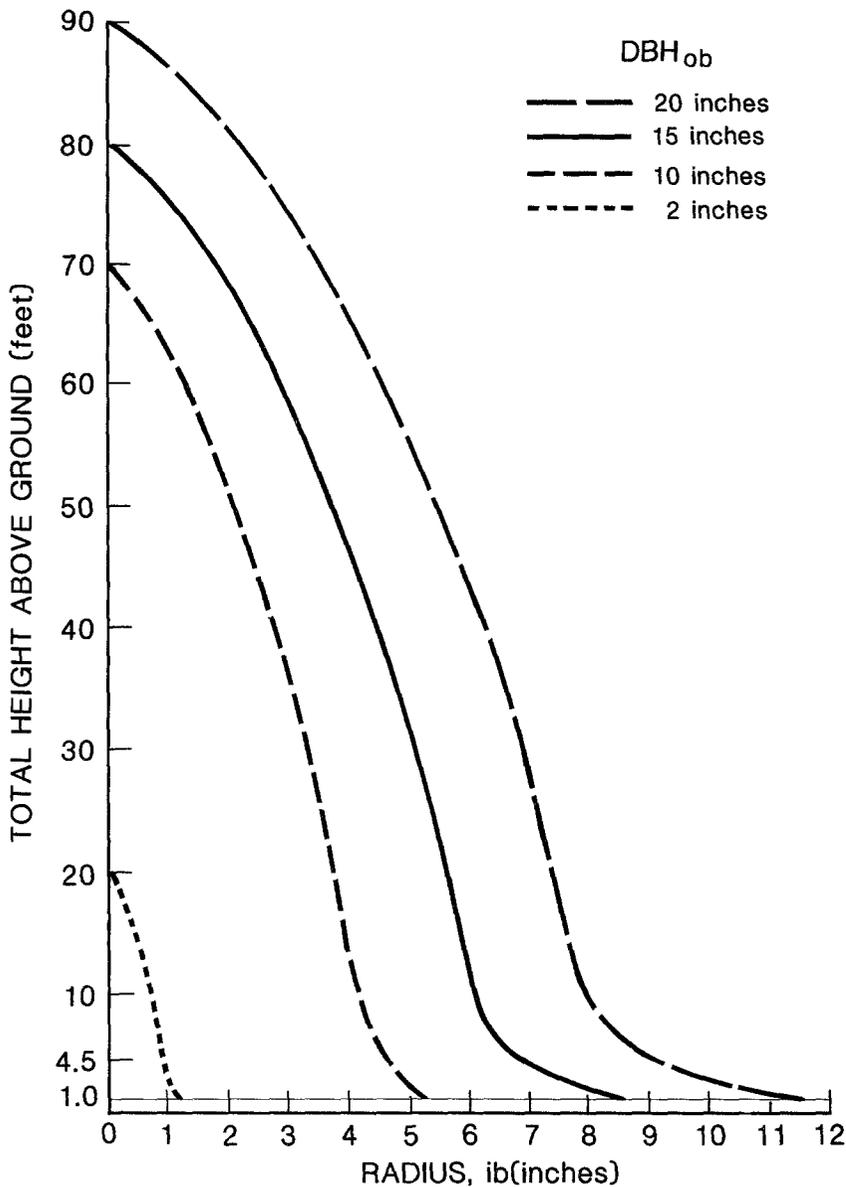


Figure 6.—Sample stem profiles generated with taper equations used in OAKSIM.

where U1 and U2 are random numbers drawn on successive occasions. The CALL statements in OAKSIM used to invoke the random number generator are based on local computing commands, and will require some modification by the user. The generator used in OAKSIM is almost identical to IBM's RANDOM Subroutine Package. If RANDOM or its local counterpart are not available, users are advised to use a well-tested random number generator.

Use of random numbers makes OAKSIM a stochastic simulator. Output is somewhat dependent on the random numbers generated and can be altered by changing the seed used to initialize the generator (although this is not recommended). The seed statement in OAKSIM is IX = 111111. Testing has revealed that changing the seed, and hence the sequence of random numbers, changes the output only slightly, especially if long projections such as 50 years are specified. Slight

variations in output reflect only the natural variation inherent in the complex growth and yield of a forest stand.

#### Example Using OAKSIM

Bracketed numbers in this section refer to annotations on the OAKSIM output in Tables 1 and 2. Output for a young white oak stand in Kentucky that was thinned to 40 percent stocking with OAKSIM appears in Table 1. Only the final summary table of the unthinned OAKSIM run for the same stand is shown in Table 2.

Control cards supplied by the user indicate that stand table input is being used for a stand that is 34 years old on site index 66 [1]. Tree volumes are desired for 4.0 and 0.0 d.i.b. tops for cubic volumes, and 8.0 and 6.0 d.i.b. tops for board-foot volumes [2]. Default values of 4.0 and 8.0 feet are used for minimum merchantable lengths of logs. Trees between 4.6 and 8.6 will be classified as poles. A sawtimber threshold d.b.h. of 8.6 inches was used in this example only so readers can make comparisons with Schnur's (1937) yield tables and Dale's (1972) GROAK projections. A threshold d.b.h. of 11.6 inches for sawtimber would be more common.

Volume computations and program output will also depend on the assignment of tree species codes to a species group, and the subsequent assignment of a height and bark ratio prediction equation to that species group [3,4]. Species group 1 in this example consisted entirely of white oaks, group 2 was black and scarlet oak, group 3 was hickory and red maple, and group 4 was shrubs, such as dogwood and sourwood.

A total of ten 5-year projections are to be made, with one initial thinning to 40 percent stocking [5,6]. All intermediate stand tables are requested, but no intermediate stock tables are desired.

The initial stock table for age 34 [7] includes a comprehensive break-

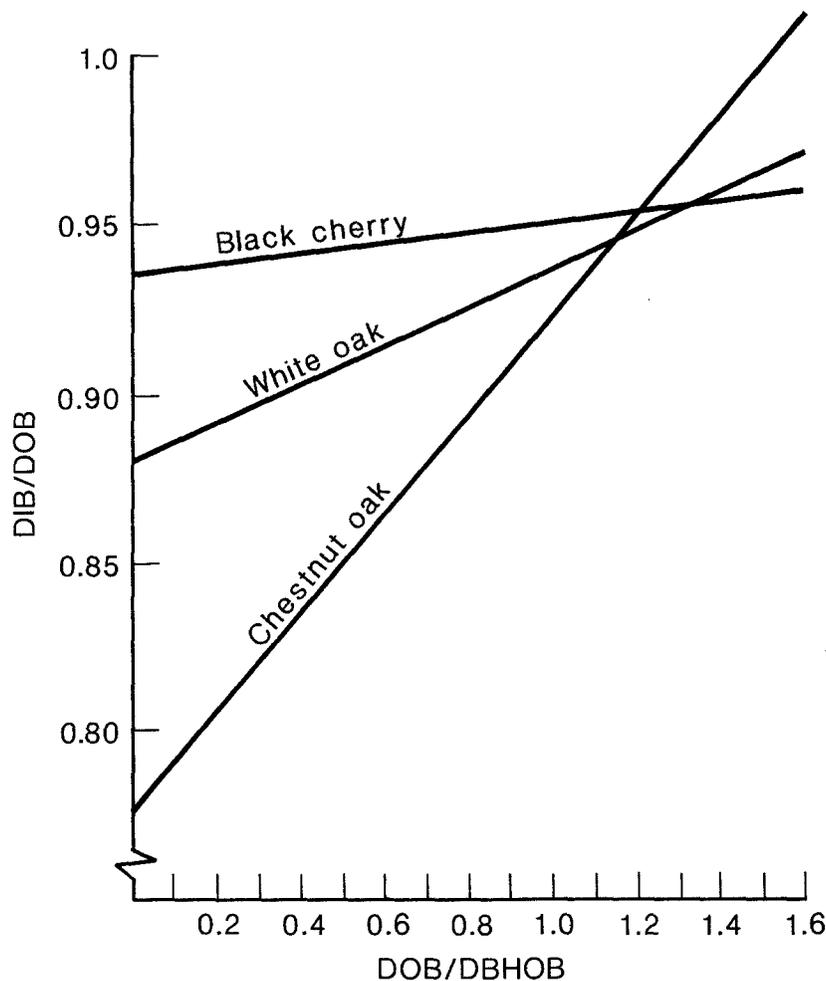


Figure 7.—DIB/DOB ratios for three species.

down by species groups and size classes for all major stand characteristics. Average d.b.h. [8] values listed in the stock tables are arithmetic means, not quadratic. The initial stock and stand [9] tables are always printed. Since all intermediate stand tables were requested for this run of OAKSIM, stand tables for trees removed in thinning [10], residual trees after thinning [11], mortality trees [12], and trees in the projected stand [13] for all 5-year intervals are printed (only those to age 39 are listed in Table 1). Final stand [14] and stock tables [15] are always printed.

It is evident from [10] that the majority of the 440 trees removed in the "free" thinning applied with the thinning rule (equation 13) were in the lower crown classes. Nearly 80 percent of the trees in the 3-inch class were cut. Some of the largest trees, however, were also removed. These larger trees are representative of the larger cull and rough trees often found in most stands. The percentage of trees by species group in each d.b.h. class, as specified with the control cards [6], remained nearly the same after thinning.

All of the detailed information available in the stand and stock tables must be utilized for a comprehensive evaluation of various thinning regimes. The size and species determine the value of a tree. For example, the changes that occurred in the white oak group should be examined closely because of the high value of this species relative to the other three groups. On the other hand, the final summary tables [16, Table 2] provide a good overall look at stand development over the projection period and is most useful for narrowing the choices of various thinning regimes.

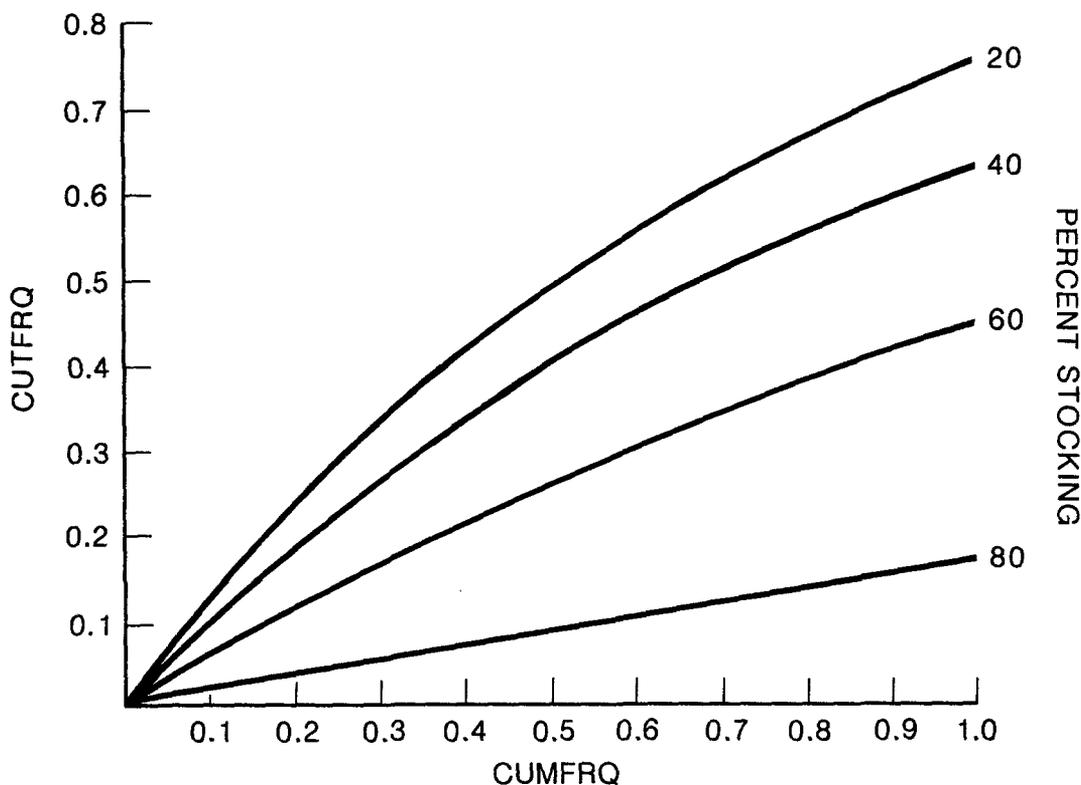


Figure 8.—Thinning rule depends on cumulative frequencies of cut trees and live trees before cut. See text for definitions of CUTFRQ and CUMFRQ.

Basal area, total cubic-foot volume inside bark, and board-foot volume growth and yield information extracted from [16] and Table 2 are plotted in Figure 9. Gross growth for the 50-year projection was reduced in the heavily thinned stand—88.7 square feet of basal area growth, compared to 104.7 for the unthinned stand, and 3017 cubic feet compared to 3389. Net growth, however, showed a marked increase in the thinned stand. Net basal area growth for the thinned stand was 69.5 square feet; in the unthinned

stand, it was only 45.7. Net cubic volume growth was 2544 cubic feet, compared to 2133. Mortality was sharply reduced with thinning, particularly for the first 25 years after thinning. Board-foot growth and yield increases from thinning are dramatic at age 84: the thinned stand had 32 percent more board-foot volume in trees 8.6 inches d.b.h. and larger. This difference was due not only to the increased diameter of the thinned trees, but also to the fact that the thinned stand had 126 trees in the sawtim-

ber size class compared to only 113 trees for the unthinned stand.

Even though gross growth rates are reduced somewhat by thinning this stand to 40 percent stocking, gains in net growth and board-foot yields indicate that a heavy thinning at age 34 is still a viable option. This run of OAKSIM also suggests another alternative: to thin initially to 40 percent and thin again at age 59 to perhaps 60 percent, since mortality started to increase at that age.

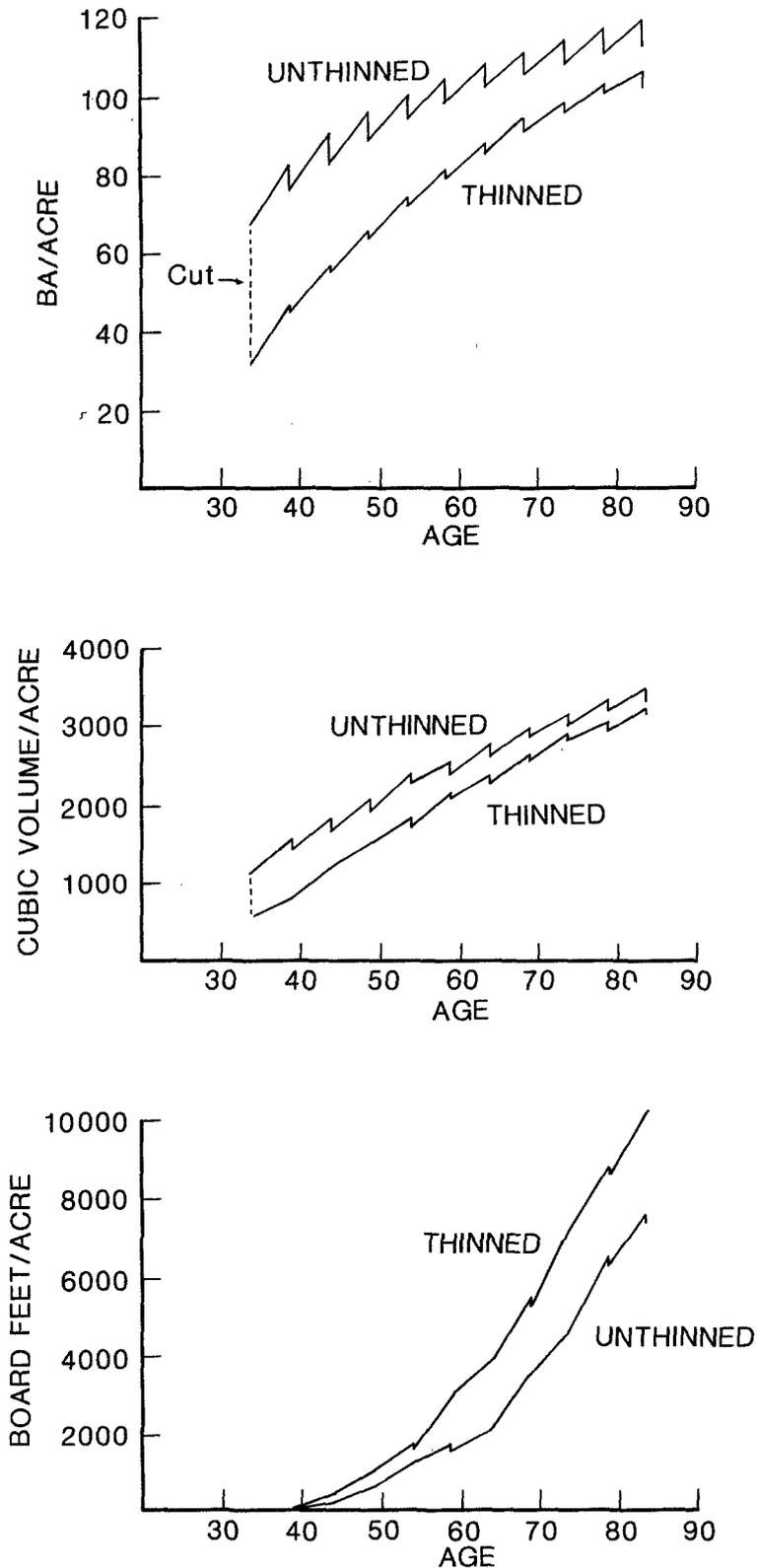


Figure 9.--Basal areas, cubic volumes (total stem inside bark), and board-foot volumes (all trees 8.6 inches and larger to a 6 inch top) per acre for sample run of OAKSIM.

## Discussion

This initial version of OAKSIM is applicable to a wide range of age, site, and stocking conditions for a large portion of the upland oak timber type. The ultimate goal is to produce a complete simulator capable of generating the entire growth cycle—not only growth of the present stand, but also ingrowth and regeneration. Ingrowth can be substantial in heavily thinned upland oak stands. And stump sprouts from ingrowth trees will most likely determine the species composition of the next stand after the rotation harvest cut. Timber management planning for the current rotation, however, should be based primarily on those trees already covered by this version of OAKSIM, not on ingrowth trees.

Future enhancements planned for OAKSIM should also encourage application of the simulator. Computer programming statements will be added to allow input from variable-plot (prism) timber cruises. This will eliminate the need for users to construct their own stand tables for input into OAKSIM. A microcomputer version of OAKSIM will also give more users access to the simulator.

This version of OAKSIM has been rigorously tested. Its net stand basal area growth is compatible with that of the previously developed stand growth and yield simulator, GROAK. However, a complete statistical validation of OAKSIM is also planned, primarily for the purpose of placing error limits on the growth and yield projections. Some measure of accuracy of the simulator is essential for large-scale applications.

## Literature Cited

OAKSIM is available from the author upon request. The program consists of approximately 1700 statements, and should be compiled to save computing costs. Control statements and data can be stored in a separate data file and read during execution. Use of a CRT screen and a text editor language package maximizes the program's flexibility. The ages and intensities of thinning can be changed easily to test a variety of management alternatives. Execution time on the AMDAHL 470 V/6 computer is approximately 10 seconds for a 50-year projection for one stand. Complete operating instructions for OAKSIM will be published in a user's guide.

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Hilt, Donald E. **OAKSIM: An individual-tree growth and yield simulator for managed, even-aged, upland oak stands.** Res. Pap. NE-562. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1985. 21 p.

OAKSIM is an individual-tree growth and yield simulator for managed, even-aged, upland oak stands. Growth and yield projections for various thinning alternatives can be made with OAKSIM for a period of up to 50 years. Simulator components include an individual-tree diameter growth model, a mortality model, height prediction equations, bark ratio equations, a taper-based volume system, and a mathematical thinning rule based on actual data. OAKSIM can be applied to a wide range of age, site, and stand conditions to develop management (thinning) guidelines.

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**Keywords:** Increment; thinning.

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