by Martin E. Dale

Growth and Yield Predictions for Upland Oak Stands

10 Years After Initial Thinning

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INTRODUCTION

THE OAK-HICKORY forest type is by far the most extensive hardwood timber type in this country. It occupies nearly 116 million acres, or about one-quarter of the commercial forest land in the United States. Although this timber type dominates the forest landscape from the Appalachian Mountains west to the Great Plains, we have little information about either the quantitative or qualitative growth and yield of thinned upland oak stands.

This seriously handicaps intensive timber management because such information is necessary for selecting from among various thinning alternatives the one practice best suited to meet a specific objective. Three types of information are needed for selecting the best alternative: (1) the change in physical yields resulting from a specific thinning practice, including quantity, quality, and timing of yields; (2) the costs incurred in applying the practice; and (3) the values of the physical yields when they occur. With such estimates the decision-maker can select objectively among alternatives, determine the relative profitability of each, and assign priorities for stand treatment.

The purpose of this paper is to furnish part of the needed information, that is, quantitative estimates of growth and yield 10 years after initial thinning of upland oak stands. All estimates are computed from a system of equations. These predictions are presented here in tabular form for convenient visual inspection of growth and yield trends. The tables show growth and yield in terms of basal area, total cubic-foot volume, cordwood volume, and board-foot volume over a broad range of site, age, and residual stand density classes.

All the equations were developed from a set of 154 permanent growth plots where responses were observed over 5- to 12-year growth periods. Many users with access to computers will find the equations more useful than tables, especially if interested in specific stand conditions not listed in the tables or for use in other computer programs. A complete discussion of equation development is beyond the scope of this paper; however, the basic regression equations are given in the Appendix.

THE STUDY

The 154 permanent plots used in developing the growth and yield predictions were established as part of eight separate growth studies, two each in Kentucky, Ohio, Missouri, and Iowa (fig. 1 and table 1). All eight groups of plots were analyzed together because the objectives, methods of treatment, and plot-selection criteria were essentially the same.

Species composition varied between series from white oak to almost pure black oak stands (table 2). Although species composition does affect growth and yield, species differences are ignored in this report. Our plot data indicated confounding between species and location, and between species and site quality; so with our sample there was insufficient plot data for separating out species effect.

Stand age at time of initial thinning varied among the growth series from 22 to 90 years, which should adequately cover ages where intermediate cutting is practiced. Site index of plots averaged 69 overall, varying from 55 to 89; but most plots (83 percent) ranged between site indexes 60 and 80. Site index was based upon Schnur's (*1937*) site-index curves for upland oak. Our distribution of sample plots by site index is typical over a large part of the natural range of upland oak.

All plots were chosen initially as representative of fully stocked even-aged upland oak stands that showed little evidence of recent fire or logging. On some plots a few older and larger trees were present, probably as holdovers from the previous stand. Site index and

Figure 1.—Location of the study plots.

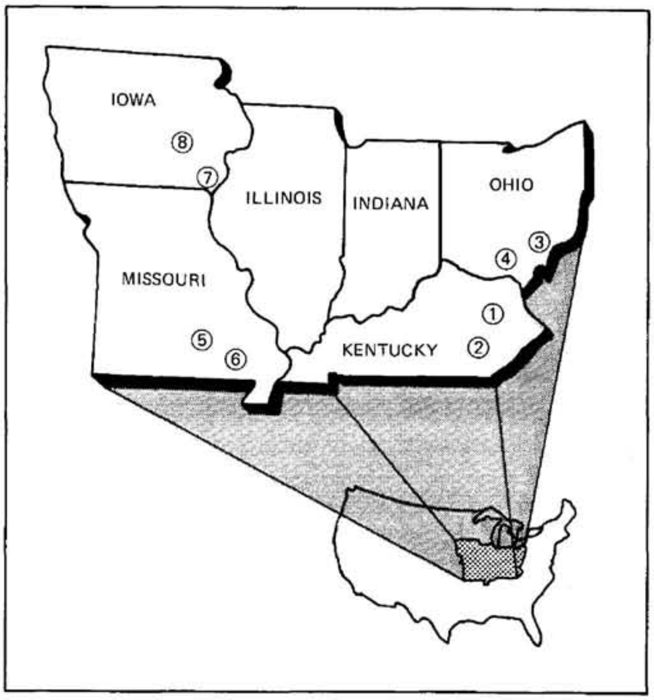

Table 1.—*Characteristics of studies used to develop growth and yield relations for upland oak*

Study No.	Study Location	Plots	Plot size	Date study started	Initial average stand age	Range of site index	Remeasurements	Years of growth used in computing average	Principal species
		No.	*Acres*		*Years*		*No.*	*Years*	
1	Kentucky	[1]6	0.5	1961	33	62-77	7	7	White oak
2	Kentucky	16	1.0	1959	80	60-68	7	7	White oak
3	Ohio	16	.5	1961	31	67-80	7	7	Mixed oak
4	Ohio	16	.5	1962	60	60-71	6	6	White oak
5	Missouri	30	.5	1962	22	61-89	1	5	Black oak
6	Missouri	30	.5	1961	40	60-84	1	6	Black oak
7	Iowa	20	.2	1949	25	55-66	5	[2]12	White oak
8	Iowa	20	1.0	1953	90	60-69	6	9	White oak

[1]Nine additional plots cut to lower density levels were eliminated from analysis because all understory stems were cut.
[2]This series received a second thinning in 1961, but response to only the first thinning is included.

Table 2.—*Basal area and number of trees for each study at beginning and ending of growth period, by species groups*[1]

[In percent]

Study No.	Date	Group 1		Group 2		Group 3		Group 4		Group 5	
		No. trees	Basal area	No. trees	Basal area	No. trees	Basal area	No. trees	Basal area	No. trees	Basal area
1	1961	77.01	73.31	13.78	17.95	0.44	1.11	5.40	5.45	3.37	2.18
	1968	79.77	75.30	10.12	16.48	.44	1.02	7.01	5.49	2.70	1.71
2	1961	76.66	84.54	2.22	3.48	1.50	1.61	13.86	8.55	5.76	1.82
	1968	73.43	84.63	2.11	3.30	2.44	1.83	15.10	8.30	6.92	1.94
3	1961	26.16	24.27	62.26	66.72	2.37	3.33	8.90	5.60	.31	.08
	1968	27.32	24.48	60.38	66.43	2.27	3.50	9.59	5.49	.44	.10
4	1962	61.55	57.87	34.78	40.37	.28	.17	3.11	1.53	.28	.06
	1968	65.80	62.74	29.33	35.29	.42	.18	3.52	1.66	.93	.13
5	1962	7.16	6.46	89.44	91.12	.03	.03	3.37	2.39	—	—
	1967	7.48	6.30	88.43	91.33	.03	.03	4.06	2.34	—	—
6	1961	11.86	8.07	83.01	88.70	.46	.41	4.63	2.81	.04	.01
	1967	12.16	7.91	82.76	89.28	.48	.37	4.56	2.43	.04	.01
7	1949	66.89	69.78	23.66	23.58	2.09	2.43	7.36	4.21	—	—
	1961	63.97	66.31	20.93	25.74	2.75	2.82	12.29	5.12	.06	.01
8	1953	88.43	89.62	6.32	6.78	1.02	.28	4.23	3.32	—	—
	1962	89.54	90.47	5.04	5.76	1.08	.33	4.34	3.44	—	—

[1]Group 1: White oak, chestnut oak.
Group 2: Black oak, scarlet oak, northern red oak.
Group 3: Black walnut, yellow-poplar, ash, basswood, sycamore, black cherry, shortleaf pine, hemlock.
Group 4: Hickory, black gum, red maple, sugar maple, post oak, blackjack oak, red elm, beech, black locust, shingle oak, hackberry.
Group 5: Dogwood, serviceberry, sourwood, ironwood, sassafras, holly, redbud, hawthorn, burr oak, mulberry, miscellaneous shrubs.

age varied little both within and between plots for a given series. Detailed measurements on no fewer than 10 sample trees per plot provided age, site, and height data at the time of plot installation. These sample trees, mostly dominant or codominant, were selected for their high potential as final crop trees and for their spatial distribution.

Similar marking rules were used for each series to create four or more stand-density levels. Cutting varied from very light or none to removing 70 or 80 percent of the original basal area, except for the older study in Iowa, where the heaviest cutting removed only about 30 percent of the basal area. After this initial cutting, plots ranged in basal area from a low of 20 to 30 square feet per acre up to between 75 and 110 square feet.

The thinning method we used resembled a selection thinning as defined by the Society of American Foresters (*1950*). However, our thinning procedure is more accurately described (*Braathe 1957*) as "free thinning," in which the marker is free to remove trees through all crown classes. Our objective was to leave a suitable number of the best stems as evenly spaced as possible over the plot. In general, we cut the larger cull and defective trees first, then competing trees of poor form and quality, then intermediate and suppressed trees of lower quality and value, and finally, if necessary, the lower value species of the main crown class. High-quality desirable species were cut also if necessary to achieve a uniform spatial distribution.

ANALYSIS

The number of years of growth data varied among different series of plots from 5 years to 12 years (table 1). Plot size also varied by series from 1/5 to 1 acre in size. In our analysis these differences were disregarded, and all plots received equal weight in the regression analyses. The Ohio State University/Econ step-wise regression program was used for all regression equations.

Averages were used for some independent variables such as basal area, age, number of trees, and plot volumes, rather than the initial or final plot values. These average values are preferable when calculus methods are used. To determine average basal area, as an example, the initial and most recent measurements were used to compute basal area by equation from the individual tree diameters for all trees greater than 2.6 inches d.b.h., summed over all trees on a plot, and expanded to a per-acre basis. Then the initial and most recent basal areas per acre were averaged to provide the average basal area per acre over the growth interval. Net annual growth in basal area and volume, expressed as the average per acre per year, was obtained as the difference between the final and initial per-acre values divided by the number of years in the growth period.

Average cubic and board-foot volumes were computed in the same manner as basal area; however, the tree-volume equations required both total tree height and tree diameter as independent variables. Therefore total tree height was estimated by regression, using sample tree data; and this estimate of height was substituted into the volume equations. Two different tree-height equations were used; one for the white oak group and one for the red oak group. All volume estimates were for gross content, and no allowances were made for defect.

The summarized plot data were used to fit several recently published growth and yield models as well as some model forms we hypothesized. In these models we tried various transformations and combinations of independent variables such as stand age, basal area, number of trees, site quality, and average stand diameter.

The models we selected for basal-area growth and total cubic-foot volume are, respectively:

$$Y_1 = -BA^{-.8} \operatorname{Ln}B + 3.68521BA^{-.75} + .011383BSA^{-1.05} \qquad [1]$$

$$Y_2 = 3.09094 + .009302S + 1.03909\operatorname{Ln}B - 20.11035A^{-1} \qquad [2]$$

where:

Y_1 = net annual basal area growth per acre in square feet for all trees 2.6 inches or larger in d.b.h.

Y_2 = natural logarithm of total cubic-foot volume per acre for all trees 2.6 inches or larger in d.b.h.

B = basal area in square feet per acre of all living trees 2.6 inches or larger in d.b.h.

S = site index in feet

A = average stand age in years.

These equations provide a statistically close fit of the data; they are simpler in form than some proposed; and the growth trends in relation to age, site, and basal area agree well with biological assumptions. Plotting residuals (actual minus predicted values) over age, site, and basal area produced no evidence of nonconformity of these models over most of the range of all variables. Statistical information for these equations is given in table 11 (appendix).

Merchantable cubic-foot and board-foot volume estimates were obtained by multiplying the total cubic-foot volume by the ratio of merchantable cubic-foot or board-foot volume to total cubic-foot volume. Cordwood volume was estimated by dividing the merchantable cubic-foot volume by 80. Both the merchantable cubic-foot and board-foot ratios increase with the average stand diameter. These relationships, described by equations 4 and 5 (table 11, appendix), were developed by regressing the volume ratio data on average stand diameter for the 154 study plots. The calculated volume ratios using equations 4 and 5 are shown in table 12 (appendix), by 1-inch d.b.h. classes. The volume ratios change most rapidly when stand diameter is near the threshold diameter (4.6 inches for cordwood and 8.6 inches for board-foot volume). Both volume ratios gradually approach constant values as stand diameter increases.

It is not feasible to give volume estimates here for all combinations of age, site, and basal area over a range of different average stand diameters. So, in the tables presented here, we used a regression equation to determine average stand diameter as a function of site and age (equation 3, table 11, appendix). Then this average stand diameter was adjusted for each site and age class to reflect changes in average stand diameter due to intensity of cutting. These adjusted average stand diameters are given in table 13 (appendix), by site, age, and residual basal area after the initial thinning. They were substituted into equations 4 and 5 to compute the volume ratios, hence these assumed average stand diameters affect the cordwood and board-foot volume estimates presented here. When stand diameters are different than those shown in table 13 the estimates of cordwood and board-foot volume will be different.

A Fortran IV computer program is available, upon request, that will provide these growth and yield estimates up to 30 years after initial thinning for any desired combination of age, site, basal area, and average stand diameter. The only program input variables required are initial stand age, basal area, number of trees above 2.6 inches d.b.h., and site index. This program includes ingrowth and mortality functions that are used to adjust the number of trees annually.

RESULTS

Growth and yield predictions are given for thinned upland oak stands in tables 3 through 10. Estimates are given by age, basal area, and site class, all in increments of 10 units; from age 20 to 110 years, from 20 to 130 square feet of basal area; and from site index 55 to 85. All values were generated by the Fortran IV computer program, which incorporated the equations listed in table 11 (appendix), along with ingrowth and mortality functions.

Table 3 gives the current annual net basal-area growth per acre for specified ages and residual basal areas for each site class. These growth estimates are the solutions one would get by substituting into equation 1 the specified ages, sites, and basal areas. For example, a stand on site 65 with a residual basal area of 50 square feet at age 30 will on the average grow 2.54 square feet between age 30 and 31. A year later, age and basal area will have changed, and so will our estimate of growth.

The 10-year estimates of net basal-area growth in table 4 were obtained by repeatedly solving equation 1, each time updating age and basal area, and summing the 10 annual growth estimates. The stand from the previous example with 50 square feet of basal area at age 30 on site 65 would increase in basal area by 21.46 square feet over 10 years, or at age 40 this stand would reach 71.46 square feet of basal area.

Estimates of total cubic-foot volume, including bark, stump, and tip of all trees 2.6 inches d.b.h. or larger, are given in table 5. These volume estimates were obtained by solving equation 2 for each combination of age, site, and basal area. Total cubic-foot volume growth for 10 years (table 6) was obtained as the difference between the initial volume estimate (using the initial age and basal area) and the volume 10 years later, (using an updated age and basal area).

For the previous stand conditions, the total cubic-foot volume at age 30 would be 1,200 cubic feet (table 5). In 10 years, at age 40, the stand would reach 71.46 square feet of basal area; so equation 2 for these stand conditions would predict a stand total volume of 2,057 cubic feet. The difference between the final and initial volumes (2,057 minus 1,200) is the net volume growth for 10 years, or 857 cubic feet as shown in table 6.

The cordwood volume shown in table 7 is the merchantable volume in cubic feet divided by 80. Merchantable cubic-foot volume pertains to the gross content of all trees 4.6 inches d.b.h. or larger, excluding the bark, stump, and branches to a 4-inch top d.i.b. Merchantable cubic-foot volume is not shown, but was calculated by multiplying the total cubic-foot volume by the ratio of merchantable to total volume. This ratio is related to average stand diameter (equation 4, table 11, appendix) and was computed for each average stand diameter given in table 13 (appendix).

An illustration using the previous stand conditions should clarify the procedure. The average stand diameter for age 30 on site 65 with 50 square feet of basal area is 5.2 inches d.b.h. (table 13, appendix). Using 5.2 inches as the average stand diameter and applying equation 4 (appendix), we predict a merchantable to total volume ratio of 0.540. Multiplying this ratio by the total cubic-foot volume (0.540 x 1,200) gives 648 merchantable cubic feet, and dividing by 80 gives 8.1 cords, as shown in table 7. Growth in cords over the next 10-year period is given in table 8 by initial age and initial basal area. Net growth in cords is the difference between the volume 10 years hence and the initial volume in cords.

The merchantable to total cubic-foot ratio

Continued on page 14

Table 3.—*Current annual basal-area increment per acre for given age and basal area*

[In square feet]

Basal area	Average stand age — years									
	20	30	40	50	60	70	80	90	100	110
					SITE INDEX 55					
20	2.88	2.16	1.76	1.51	1.32	1.19	1.08	1.00	0.93	0.87
30	3.21	2.44	2.01	1.73	1.53	1.38	1.26	1.16	1.08	1.02
40	3.23	2.49	2.07	1.80	1.60	1.45	1.33	1.23	1.15	1.09
50	3.03	2.38	2.01	1.76	1.58	1.44	1.33	1.24	1.16	1.10
60	2.63	2.14	1.84	1.63	1.48	1.36	1.27	1.19	1.12	1.06
70	2.09	1.78	1.58	1.43	1.32	1.23	1.15	1.09	1.04	.99
80	—	1.34	1.25	1.17	1.10	1.05	1.00	.95	.92	.88
90	—	—	.85	.85	.84	.82	.80	.78	.76	.74
100	—	—	—	—	.54	.56	.58	.58	.58	.58
110	—	—	—	—	—	—	.32	.35	.38	.40
120	—	—	—	—	—	—	—	—	—	.19
					SITE INDEX 65					
20	2.98	2.22	1.81	1.54	1.36	1.21	1.10	1.02	0.94	0.88
30	3.36	2.53	2.08	1.78	1.57	1.42	1.29	1.19	1.11	1.04
40	3.43	2.62	2.17	1.87	1.66	1.50	1.38	1.27	1.19	1.12
50	3.27	2.54	2.13	1.85	1.66	1.51	1.39	1.29	1.21	1.14
60	2.93	2.33	1.98	1.75	1.57	1.44	1.34	1.25	1.17	1.11
70	2.43	2.01	1.75	1.56	1.43	1.32	1.23	1.16	1.10	1.05
80	—	1.59	1.44	1.32	1.23	1.15	1.09	1.03	.99	.95
90	—	—	1.06	1.02	.98	.94	.91	.87	.84	.82
100	—	—	—	.68	.69	.70	.69	.68	.67	.66
110	—	—	—	—	—	.41	.45	.47	.48	.49
120	—	—	—	—	—	—	—	.22	.26	.29
130	—	—	—	—	—	—	—	—	—	.07
					SITE INDEX 75					
20	3.07	2.29	1.86	1.58	1.39	1.24	1.13	1.04	0.96	0.90
30	3.50	2.63	2.15	1.84	1.62	1.45	1.33	1.22	1.14	1.06
40	3.62	2.75	2.26	1.95	1.72	1.56	1.42	1.32	1.23	1.15
50	3.52	2.70	2.25	1.95	1.73	1.57	1.44	1.34	1.25	1.18
60	3.22	2.52	2.12	1.86	1.67	1.52	1.40	1.31	1.23	1.16
70	2.78	2.23	1.91	1.70	1.54	1.41	1.31	1.23	1.16	1.10
80	2.20	1.85	1.63	1.47	1.35	1.26	1.18	1.12	1.06	1.01
90	—	1.38	1.28	1.19	1.12	1.06	1.01	.97	.93	.89
100	—	—	.87	.86	.85	.83	.81	.78	.76	.74
110	—	—	—	—	.53	.56	.57	.58	.58	.58
120	—	—	—	—	—	—	.31	.34	.37	.38
130	—	—	—	—	—	—	—	—	.14	.17
					SITE INDEX 85					
20	3.17	2.35	1.90	1.62	1.42	1.27	1.15	1.06	0.98	0.91
30	3.65	2.73	2.22	1.89	1.67	1.49	1.36	1.25	1.16	1.09
40	3.82	2.88	2.36	2.02	1.79	1.61	1.47	1.36	1.26	1.18
50	3.76	2.86	2.36	2.04	1.81	1.64	1.50	1.39	1.30	1.22
60	3.52	2.71	2.26	1.97	1.76	1.60	1.47	1.37	1.28	1.21
70	3.12	2.46	2.08	1.83	1.64	1.50	1.39	1.30	1.23	1.16
80	2.59	2.10	1.82	1.62	1.48	1.36	1.27	1.20	1.13	1.08
90	—	1.67	1.49	1.36	1.26	1.18	1.11	1.06	1.01	.96
100	—	—	1.10	1.05	1.00	.96	.92	.89	.85	.83
110	—	—	—	.70	.71	.70	.70	.69	.68	.67
120	—	—	—	—	—	.42	.45	.46	.48	.48
130	—	—	—	—	—	—	—	.22	.25	.28

Table 4.—*Net basal-area growth in 10 years, by initial age and basal area*

[In square feet per acre]

Initial basal area	Initial stand age — years									
	20	30	40	50	60	70	80	90	100	110
					SITE INDEX 55					
20	27.76	21.82	18.16	15.67	13.85	12.46	11.35	10.46	9.71	9.08
30	27.84	22.61	19.23	16.85	15.08	13.70	12.59	11.68	10.91	10.26
40	26.12	21.81	18.91	16.81	15.21	13.94	12.91	12.05	11.32	10.69
50	23.27	19.99	17.67	15.93	14.58	13.48	12.58	11.82	11.16	10.59
60	19.62	17.42	15.75	14.44	13.38	12.50	11.76	11.13	10.58	10.10
70	15.37	14.29	13.31	12.46	11.74	11.11	10.57	10.09	9.66	9.28
80	—	10.70	10.44	10.09	9.73	9.38	9.05	8.74	8.46	8.20
90	—	—	7.21	7.39	7.41	7.35	7.26	7.14	7.02	6.89
100	—	—	—	—	4.83	5.08	5.24	5.32	5.36	5.37
110	—	—	—	—	—	—	3.01	3.31	3.53	3.69
120	—	—	—	—	—	—	—	—	—	1.85
					SITE INDEX 65					
20	29.06	22.68	18.79	16.16	14.25	12.79	11.64	10.71	9.93	9.28
30	29.43	23.70	20.05	17.50	15.62	14.16	12.99	12.03	11.22	10.54
40	27.96	23.11	19.90	17.60	15.87	14.50	13.40	12.48	11.71	11.04
50	25.33	21.46	18.81	16.86	15.35	14.15	13.16	12.34	11.63	11.02
60	21.87	19.07	17.04	15.49	14.27	13.27	12.44	11.73	11.12	10.59
70	17.79	16.08	14.73	13.63	12.73	11.97	11.32	10.76	10.27	9.84
80	—	12.64	11.99	11.37	10.82	10.33	9.89	9.49	9.14	8.82
90	—	—	8.88	8.78	8.60	8.39	8.18	7.97	7.76	7.57
100	—	—	—	5.90	6.11	6.21	6.24	6.22	6.18	6.12
110	—	—	—	—	—	3.81	4.09	4.28	4.41	4.50
120	—	—	—	—	—	—	—	2.16	2.47	2.71
130	—	—	—	—	—	—	—	—	—	.79
					SITE INDEX 75					
20	30.38	23.55	19.43	16.65	14.65	13.13	11.93	10.96	10.16	9.48
30	31.06	24.81	20.88	18.16	16.16	14.62	13.38	12.38	11.53	10.82
40	29.85	24.42	20.90	18.41	16.54	15.08	13.90	12.92	12.10	11.40
50	27.43	22.97	19.97	17.80	16.14	14.83	13.75	12.86	12.10	11.44
60	24.18	20.74	18.34	16.56	15.17	14.04	13.12	12.34	11.67	11.09
70	20.28	17.92	16.17	14.82	13.73	12.84	12.09	11.45	10.89	10.40
80	15.89	14.62	13.56	12.67	11.93	11.29	10.74	10.25	9.83	9.45
90	—	10.93	10.58	10.19	9.80	9.44	9.11	8.80	8.52	8.26
100	—	—	7.30	7.42	7.41	7.35	7.24	7.13	7.00	6.87
110	—	—	—	—	4.79	5.03	5.17	5.25	5.29	5.31
120	—	—	—	—	—	—	2.91	3.21	3.42	3.59
130	—	—	—	—	—	—	—	—	1.40	1.72
					SITE INDFX 85					
20	31.74	24.44	20.07	17.15	15.06	13.47	12.22	11.22	10.38	9.68
30	32.74	25.94	21.72	18.83	16.71	15.08	13.78	12.73	11.85	11.10
40	31.78	25.77	21.92	19.22	17.21	15.65	14.40	13.36	12.49	11.75
50	29.60	24.50	21.15	18.75	16.94	15.51	14.35	13.39	12.57	11.87
60	26.55	22.45	19.67	17.64	16.07	14.83	13.80	12.95	12.22	11.58
70	22.84	19.79	17.63	16.02	14.75	13.72	12.86	12.14	11.51	10.97
80	18.62	16.64	15.16	13.99	13.04	12.26	11.59	11.02	10.52	10.08
90	—	13.10	12.31	11.62	11.02	10.50	10.05	9.64	9.28	8.95
100	—	—	9.14	8.95	8.73	8.49	8.26	8.04	7.83	7.63
110	—	—	—	6.03	6.19	6.26	6.27	6.24	6.19	6.13
120	—	—	—	—	—	3.83	4.08	4.26	4.38	4.46
130	—	—	—	—	—	—	—	2.12	2.42	2.66

Table 5.—*Total cubic-foot volume of all trees over 2.5 inches d.b.h., by age and basal area*

[In cubic feet]

Basal area	Average stand age — years									
	20	30	40	50	60	70	80	90	100	110
					SITE INDEX 55					
20	302	422	499	552	590	619	642	660	675	687
30	460	643	760	841	899	943	978	1,005	1,028	1,047
40	620	867	1,025	1,134	1,213	1,272	1,318	1,356	1,386	1,412
50	782	1,093	1,293	1,430	1,529	1,604	1,663	1,710	1,748	1,781
60	945	1,322	1,563	1,728	1,848	1,938	2,009	2,066	2,113	2,152
70	1,109	1,551	1,834	2,028	2,169	2,275	2,358	2,425	2,480	2,526
80	—	1,782	2,107	2,330	2,492	2,614	2,709	2,786	2,849	2,902
90	—	—	2,381	2,633	2,816	2,954	3,062	3,149	3,220	3,279
100	—	—	—	—	3,142	3,296	3,416	3,513	3,593	3,659
110	—	—	—	—	—	—	3,772	3,879	3,967	4,040
120	—	—	—	—	—	—	—	—	—	4,422
					SITE INDEX 65					
20	331	463	548	606	648	679	704	724	740	754
30	505	706	835	923	987	1,035	1,073	1,104	1,128	1,149
40	681	952	1,125	1,244	1,331	1,396	1,447	1,488	1,522	1,550
50	858	1,200	1,419	1,569	1,678	1,760	1,825	1,876	1,919	1,954
60	1,037	1,450	1,715	1,896	2,028	2,127	2,205	2,268	2,319	2,362
70	1,218	1,702	2,013	2,226	2,380	2,497	2,588	2,662	2,722	2,772
80	—	1,956	2,313	2,557	2,734	2,869	2,973	3,058	3,127	3,185
90	—	—	2,614	2,890	3,091	3,242	3,361	3,456	3,534	3,599
100	—	—	—	3,225	3,448	3,617	3,749	3,856	3,943	4,016
110	—	—	—	—	—	3,994	4,140	4,257	4,353	4,434
120	—	—	—	—	—	—	—	4,660	4,765	4,853
130	—	—	—	—	—	—	—	—	—	5,274
					SITE INDEX 75					
20	364	508	601	665	711	746	773	795	813	828
30	554	775	916	1,013	1,083	1,136	1,178	1,211	1,238	1,261
40	747	1,045	1,235	1,366	1,460	1,532	1,588	1,633	1,670	1,701
50	942	1,317	1,557	1,722	1,842	1,932	2,002	2,059	2,106	2,145
60	1,138	1,592	1,882	2,081	2,226	2,335	2,420	2,489	2,545	2,592
70	1,336	1,868	2,209	2,443	2,612	2,740	2,841	2,921	2,987	3,042
80	1,535	2,146	2,538	2,806	3,001	3,148	3,263	3,356	3,432	3,495
90	—	2,426	2,868	3,172	3,392	3,558	3,688	3,793	3,878	3,950
100	—	—	3,200	3,539	3,784	3,970	4,115	4,231	4,327	4,407
110	—	—	—	—	4,178	4,383	4,543	4,672	4,778	4,866
120	—	—	—	—	—	—	4,973	5,114	5,230	5,326
130	—	—	—	—	—	—	—	—	5,683	5,788
					SITE INDEX 85					
20	399	558	660	729	780	818	848	872	892	908
30	608	850	1,005	1,112	1,189	1,247	1,293	1,329	1,359	1,384
40	820	1,146	1,355	1,499	1,603	1,681	1,743	1,792	1,833	1,867
50	1,034	1,445	1,709	1,890	2,021	2,120	2,198	2,260	2,311	2,354
60	1,249	1,747	2,066	2,284	2,443	2,562	2,656	2,731	2,793	2,845
70	1,467	2,050	2,425	2,681	2,867	3,008	3,117	3,206	3,278	3,339
80	1,685	2,356	2,785	3,080	3,294	3,455	3,581	3,683	3,766	3,836
90	—	2,662	3,148	3,481	3,722	3,905	4,048	4,162	4,256	4,335
100	—	—	3,512	3,884	4,153	4,357	4,516	4,644	4,749	4,837
110	—	—	—	4,288	4,585	4,810	4,986	5,127	5,243	5,340
120	—	—	—	—	—	5,266	5,458	5,613	5,739	5,845
130	—	—	—	—	—	—	—	6,099	6,237	6,352

Table 6.—*Net cubic-volume growth per acre in 10 years, by initial age and basal area*

[In cubic feet per acre]

Initial basal area	Initial stand age — years									
	20	30	40	50	60	70	80	90	100	110
					SITE INDEX 55					
20	741	652	581	525	479	442	411	385	362	342
30	812	720	646	588	541	502	469	441	417	396
40	842	745	670	612	565	527	495	467	443	422
50	844	740	665	608	563	527	496	470	447	427
60	828	715	639	584	542	508	479	455	435	416
70	797	673	596	543	504	473	448	427	409	393
80	—	619	540	489	453	426	405	387	372	359
90	—	—	472	423	391	368	351	337	325	315
100	—	—	—	—	320	301	288	278	270	264
110	—	—	—	—	—	—	217	212	208	205
120	—	—	—	—	—	—	—	—	—	140
					SITE INDEX 65					
20	845	741	658	593	540	498	462	432	406	384
30	931	822	736	668	613	568	530	498	470	446
40	970	856	768	699	645	600	562	530	502	477
50	979	857	768	700	647	604	567	536	510	486
60	966	834	744	678	627	587	553	524	499	477
70	937	793	701	638	590	553	522	496	474	455
80	—	738	644	582	538	505	478	456	437	420
90	—	—	573	514	474	445	422	404	388	375
100	—	—	—	435	399	374	356	342	331	321
110	—	—	—	—	—	295	282	272	265	259
120	—	—	—	—	—	—	—	194	192	190
130	—	—	—	—	—	—	—	—	—	115
					SITE INDEX 75					
20	964	841	744	669	609	560	519	485	456	430
30	1,067	939	838	758	695	643	599	562	530	502
40	1,117	982	879	799	735	682	638	601	568	540
50	1,133	990	884	805	742	691	648	612	580	553
60	1,124	971	864	786	725	677	636	602	573	547
70	1,098	931	822	746	689	643	606	575	548	525
80	1,056	875	764	690	636	595	562	534	510	490
90	—	806	692	620	570	533	504	481	461	444
100	—	—	607	537	492	460	436	416	401	388
110	—	—	—	—	403	376	357	343	332	323
120	—	—	—	—	—	—	270	261	254	250
130	—	—	—	—	—	—	—	—	170	170
					SITE INDEX 85					
20	1,099	954	842	755	686	630	583	544	511	482
30	1,222	1,070	952	860	787	726	676	634	597	565
40	1,285	1,126	1,005	911	836	775	724	680	643	610
50	1,310	1,141	1,018	924	850	790	740	697	660	628
60	1,307	1,127	1,001	908	837	779	731	690	656	625
70	1,283	1,090	961	870	802	747	702	665	633	605
80	1,243	1,034	903	814	749	698	658	624	595	570
90	—	963	829	742	681	635	599	569	544	522
100	—	—	741	656	599	558	527	502	482	464
110	—	—	—	559	507	471	445	425	409	396
120	—	—	—	—	—	373	353	339	328	319
130	—	—	—	—	—	—	—	244	238	235

Table 7.—*Total cordwood volume per acre of all trees over 4.5 inches d.b.h., by age and basal area*

[In cords per acre]

Basal area	Average stand age — years									
	20	30	40	50	60	70	80	90	100	110
					SITE INDEX 55					
20	0.8	2.6	4.0	4.9	5.4	5.7	5.9	6.1	6.2	6.3
30	1.3	3.9	6.1	7.4	8.2	8.7	9.0	9.2	9.4	9.6
40	1.5	5.0	8.1	9.9	11.0	11.7	12.1	12.5	12.7	13.0
50	1.7	5.9	9.9	12.4	13.8	14.7	15.3	15.7	16.1	16.4
60	1.8	6.7	11.6	14.8	16.6	17.7	18.4	19.0	19.4	19.8
70	1.8	7.3	13.0	17.0	19.4	20.7	21.6	22.3	22.8	23.2
80	—	7.7	14.4	19.2	22.1	23.8	24.8	25.6	26.2	26.7
90	—	—	15.6	21.3	24.7	26.8	28.0	28.9	29.6	30.1
100	—	—	—	—	27.4	29.8	31.2	32.2	33.0	33.6
110	—	—	—	—	—	—	34.4	35.6	36.4	37.1
120	—	—	—	—	—	—	—	—	—	40.6
					SITE INDEX 65					
20	1.4	3.4	4.8	5.5	5.9	6.2	6.5	6.7	6.8	6.9
30	2.0	5.1	7.2	8.4	9.1	9.5	9.9	10.1	10.4	10.6
40	2.5	6.7	9.7	11.3	12.2	12.8	13.3	13.7	14.0	14.2
50	2.9	8.1	12.0	14.2	15.4	16.2	16.8	17.2	17.6	18.0
60	3.2	9.4	14.3	17.0	18.5	19.5	20.3	20.8	21.3	21.7
70	3.3	10.5	16.4	19.8	21.7	22.9	23.8	24.5	25.0	25.5
80	—	11.4	18.4	22.6	24.9	26.3	27.3	28.1	28.7	29.3
90	—	—	20.3	25.3	28.0	29.7	30.9	31.7	32.5	33.1
100	—	—	—	27.9	31.2	33.1	34.4	35.4	36.2	36.9
110	—	—	—	—	—	36.5	38.0	39.1	40.0	40.7
120	—	—	—	—	—	—	—	42.8	43.8	44.6
130	—	—	—	—	—	—	—	—	—	48.4
					SITE INDEX 75					
20	1.9	4.1	5.4	6.1	6.5	6.8	7.1	7.3	7.5	7.6
30	2.9	6.3	8.2	9.3	9.9	10.4	10.8	11.1	11.4	11.6
40	3.7	8.3	11.1	12.5	13.4	14.1	14.6	15.0	15.3	15.6
50	4.3	10.2	13.8	15.7	16.9	17.7	18.4	18.9	19.3	19.7
60	4.8	12.0	16.6	19.0	20.4	21.4	22.2	22.9	23.4	23.8
70	5.2	13.6	19.2	22.2	24.0	25.2	26.1	26.8	27.4	27.9
80	5.4	15.0	21.8	25.4	27.5	28.9	30.0	30.8	31.5	32.1
90	—	16.3	24.3	28.6	31.1	32.7	33.9	34.8	35.6	36.3
100	—	—	26.8	31.8	34.6	36.5	37.8	38.9	39.8	40.5
110	—	—	—	—	38.2	40.2	41.7	42.9	43.9	44.7
120	—	—	—	—	—	—	45.7	47.0	48.0	48.9
130	—	—	—	—	—	—	—	—	52.2	53.2
					SITE INDEX 85					
20	2.5	4.8	6.0	6.7	7.2	7.5	7.8	8.0	8.2	8.3
30	3.8	7.3	9.2	10.2	10.9	11.5	11.9	12.2	12.5	12.7
40	4.9	9.8	12.3	13.8	14.7	15.4	16.0	16.5	16.8	17.1
50	5.9	12.1	15.5	17.3	18.6	19.5	20.2	20.8	21.2	21.6
60	6.7	14.4	18.7	21.0	22.4	23.5	24.4	25.1	25.7	26.1
70	7.3	16.5	21.8	24.6	26.3	27.6	28.6	29.5	30.1	30.7
80	7.8	18.5	24.9	28.2	30.2	31.7	32.9	33.8	34.6	35.2
90	—	20.3	27.9	31.8	34.2	35.9	37.2	38.2	39.1	39.8
100	—	—	30.9	35.4	38.1	40.0	41.5	42.7	43.6	44.4
110	—	—	—	39.1	42.1	44.2	45.8	47.1	48.2	49.1
120	—	—	—	—	—	48.4	50.1	51.6	52.7	53.7
130	—	—	—	—	—	—	—	56.0	57.3	58.4

Table 8.—*Net cordwood growth per acre in 10 years, by initial age and basal area*

[In cords per acre]

Initial basal area	Initial stand age — years									
	20	30	40	50	60	70	80	90	100	110
					SITE INDEX 55					
20	5.9	6.4	5.7	5.0	4.4	4.1	3.8	3.5	3.3	3.1
30	5.4	7.1	6.4	5.6	5.0	4.6	4.3	4.1	3.8	3.6
40	4.3	7.2	6.8	5.9	5.3	4.9	4.5	4.3	4.1	3.9
50	2.9	6.9	6.9	6.0	5.3	4.9	4.6	4.3	4.1	3.9
60	1.5	6.4	6.8	5.9	5.2	4.7	4.4	4.2	4.0	3.8
70	.2	5.6	6.5	5.7	4.9	4.4	4.1	3.9	3.8	3.6
80	—	4.7	6.2	5.4	4.6	4.1	3.8	3.6	3.4	3.3
90	—	—	5.7	5.0	4.2	3.6	3.3	3.1	3.0	2.9
100	—	—	—	—	3.7	3.0	2.7	2.6	2.5	2.4
110	—	—	—	—	—	—	2.1	2.0	1.9	1.9
120	—	—	—	—	—	—	—	—	—	1.3
					SITE INDEX 65					
20	8.0	7.4	6.3	5.5	5.0	4.6	4.2	4.0	3.7	3.5
30	8.2	8.3	7.1	6.2	5.6	5.2	4.9	4.6	4.3	4.1
40	7.6	8.8	7.5	6.6	5.9	5.5	5.2	4.9	4.6	4.4
50	6.6	9.0	7.7	6.6	6.0	5.6	5.2	4.9	4.7	4.5
60	5.2	8.8	7.7	6.5	5.8	5.4	5.1	4.8	4.6	4.4
70	3.7	8.5	7.6	6.3	5.5	5.1	4.8	4.6	4.4	4.2
80	—	8.0	7.4	6.0	5.1	4.7	4.4	4.2	4.0	3.9
90	—	—	7.0	5.5	4.6	4.1	3.9	3.7	3.6	3.4
100	—	—	—	5.0	4.0	3.5	3.3	3.1	3.0	3.0
110	—	—	—	—	—	2.8	2.6	2.5	2.4	2.4
120	—	—	—	—	—	—	—	1.8	1.8	1.7
130	—	—	—	—	—	—	—	—	—	1.1
					SITE INDEX 75					
20	9.6	8.2	6.9	6.2	5.6	5.1	4.8	4.5	4.2	4.0
30	10.5	9.3	7.9	7.0	6.4	5.9	5.5	5.2	4.9	4.6
40	10.6	9.9	8.3	7.4	6.8	6.3	5.9	5.5	5.2	5.0
50	10.2	10.3	8.5	7.5	6.8	6.3	6.0	5.6	5.3	5.1
60	9.3	10.4	8.5	7.3	6.7	6.2	5.8	5.5	5.3	5.0
70	8.1	10.3	8.3	7.0	6.4	5.9	5.6	5.3	5.0	4.8
80	6.7	10.0	8.0	6.6	5.9	5.5	5.2	4.9	4.7	4.5
90	—	9.6	7.6	6.1	5.3	4.9	4.6	4.4	4.2	4.1
100	—	—	7.0	5.4	4.6	4.2	4.0	3.8	3.7	3.6
110	—	—	—	—	3.8	3.5	3.3	3.1	3.0	3.0
120	—	—	—	—	—	—	2.5	2.4	2.3	2.3
130	—	—	—	—	—	—	—	—	1.6	1.6
					SITE INDEX 85					
20	11.0	9.1	7.8	6.9	6.3	5.8	5.4	5.0	4.7	4.4
30	12.3	10.3	8.8	7.9	7.2	6.7	6.2	5.8	5.5	5.2
40	12.9	11.0	9.3	8.4	7.7	7.1	6.7	6.3	5.9	5.6
50	13.1	11.4	9.5	8.5	7.8	7.3	6.8	6.4	6.1	5.8
60	12.8	11.5	9.5	8.4	7.7	7.2	6.7	6.3	6.0	5.7
70	12.2	11.5	9.2	8.1	7.4	6.9	6.5	6.1	5.8	5.6
80	11.3	11.2	8.9	7.6	6.9	6.4	6.0	5.7	5.5	5.2
90	—	10.9	8.4	7.0	6.3	5.8	5.5	5.2	5.0	4.8
100	—	—	7.7	6.2	5.5	5.1	4.8	4.6	4.4	4.3
110	—	—	—	5.4	4.7	4.3	4.1	3.9	3.8	3.6
120	—	—	—	—	—	3.4	3.2	3.1	3.0	2.9
130	—	—	—	—	—	—	—	2.2	2.2	2.2

Table 9.—*Total board-foot volume per acre of all trees over 8.5 inches d.b.h., by age and basal area*

[In board feet per acre]

Basal area	Average stand age — years									
	20	30	40	50	60	70	80	90	100	110
					SITE INDEX 55					
20	0	0	118	411	898	1,431	1,870	2,178	2,359	2,434
30	0	0	168	619	1,335	2,134	2,850	3,320	3,587	3,709
40	0	0	186	727	1,651	2,708	3,696	4,401	4,789	4,988
50	0	0	175	770	1,834	3,156	4,397	5,361	5,968	6,263
60	0	0	156	777	1,936	3,490	4,997	6,267	7,049	7,507
70	0	0	119	743	1,954	3,646	5,451	6,966	8,071	8,718
80	—	0	83	690	1,929	3,728	5,767	7,601	8,989	9,858
90	—	—	43	630	1,858	3,749	6,008	8,125	9,791	10,940
100	—	—	—	—	1,824	3,808	6,225	8,595	10,574	12,001
110	—	—	—	—	—	—	6,462	9,123	11,348	13,007
120	—	—	—	—	—	—	—	—	—	14,045
					SITE INDEX 65					
20	0	42	325	888	1,545	2,076	2,420	2,558	2,628	2,677
30	0	61	465	1,304	2,330	3,164	3,646	3,893	4,005	4,080
40	0	59	553	1,602	2,929	4,119	4,851	5,234	5,400	5,501
50	0	43	572	1,772	3,394	4,922	5,985	6,552	6,801	6,937
60	0	22	568	1,866	3,783	5,669	7,027	7,820	8,200	8,383
70	0	0	523	1,859	3,976	6,201	7,960	9,042	9,587	9,836
80	0	0	475	1,836	4,084	6,630	8,774	10,175	10,934	11,289
90	—	—	419	1,768	4,122	6,914	9,463	11,241	12,238	12,727
100	—	—	—	1,736	4,167	7,267	10,144	12,238	13,521	14,163
110	—	—	—	—	—	7,538	10,764	13,218	14,789	15,580
120	—	—	—	—	—	—	—	14,293	16,048	17,007
130	—	—	—	—	—	—	—	—	—	18,451
					SITE INDEX 75					
20	0	135	654	1,439	2,172	2,562	2,737	2,821	2,885	2,938
30	0	195	960	2,192	3,260	3,891	4,171	4,299	4,396	4,478
40	0	219	1,155	2,716	4,256	5,171	5,610	5,797	5,928	6,038
50	0	215	1,262	3,160	5,093	6,378	7,028	7,308	7,475	7,613
60	0	195	1,318	3,447	5,818	7,534	8,421	8,825	9,034	9,201
70	0	156	1,277	3,563	6,318	8,532	9,776	10,332	10,603	10,800
80	0	117	1,224	3,648	6,770	9,402	11,052	11,831	12,179	12,407
90	—	76	1,161	3,643	7,073	10,137	12,221	13,291	13,756	14,022
100	—	—	1,116	3,680	7,345	10,920	13,358	14,731	15,332	15,644
110	—	—	—	—	7,637	11,640	14,528	16,130	16,900	17,272
120	—	—	—	—	—	—	15,691	17,575	18,483	18,905
130	—	—	—	—	—	—	—	—	20,058	20,544
					SITE INDEX 85					
20	2	296	1,119	2,072	2,650	2,898	3,011	3,096	3,166	3,225
30	0	429	1,645	3,075	4,003	4,409	4,588	4,718	4,825	4,914
40	0	503	2,024	3,975	5,333	5,928	6,187	6,362	6,506	6,626
50	0	524	2,276	4,710	6,537	7,423	7,800	8,023	8,204	8,355
60	0	515	2,423	5,280	7,628	8,916	9,422	9,696	9,915	10,098
70	0	471	2,459	5,693	8,590	10,287	11,035	11,380	11,638	11,852
80	0	423	2,439	5,968	9,418	11,623	12,640	13,073	13,370	13,616
90	—	367	2,397	6,169	10,171	12,847	14,204	14,771	15,110	15,389
100	—	—	2,373	6,354	10,793	14,041	15,746	16,470	16,859	17,170
110	—	—	—	6,566	11,478	15,219	17,273	18,168	18,613	18,957
120	—	—	—	—	—	16,444	18,821	19,873	20,374	20,751
130	—	—	—	—	—	—	—	21,580	22,141	22,551

Table 10.—*Net board-foot growth per acre in 10 years, by initial age and basal area*

[In board feet per acre]

Initial basal area	Initial stand age — years									
	20	30	40	50	60	70	80	90	100	110
					SITE INDEX 55					
20	0	388	962	1,458	1,744	1,742	1,596	1,434	1,304	1,218
30	0	306	947	1,596	1,939	1,955	1,819	1,643	1,502	1,408
40	0	201	838	1,558	2,028	2,096	1,938	1,733	1,587	1,493
50	0	102	690	1,442	2,007	2,160	2,014	1,783	1,602	1,499
60	0	21	564	1,305	1,933	2,169	2,046	1,793	1,578	1,453
70	0	0	441	1,151	1,822	2,130	2,049	1,780	1,523	1,369
80	—	0	347	1,006	1,704	2,075	2,036	1,754	1,452	1,256
90	—	—	270	881	1,581	2,012	2,017	1,726	1,378	1,127
100	—	—	—	—	1,487	1,962	1,998	1,698	1,300	990
110	—	—	—	—	—	—	1,981	1,664	1,218	849
120	—	—	—	—	—	—	—	—	—	701
					SITE INDEX 65					
20	234	1,086	2,023	2,431	2,320	2,008	1,713	1,546	1,442	1,362
30	90	1,000	2,150	2,796	2,730	2,346	2,009	1,791	1,671	1,584
40	0	815	2,095	2,959	3,014	2,612	2,196	1,921	1,783	1,694
50	0	625	1,904	2,969	3,193	2,820	2,329	1,988	1,818	1,726
60	0	473	1,700	2,896	3,299	2,965	2,429	2,018	1,798	1,696
70	0	329	1,462	2,743	3,336	3,092	2,511	2,017	1,738	1,618
80	—	205	1,243	2,528	3,323	3,188	2,585	2,012	1,659	1,503
90	—	—	1,039	2,244	3,157	3,268	2,659	1,997	1,566	1,365
100	—	—	—	1,994	2,948	3,183	2,708	1,979	1,453	1,198
110	—	—	—	—	—	3,051	2,682	1,944	1,322	1,017
120	—	—	—	—	—	—	—	1,840	1,175	810
130	—	—	—	—	—	—	—	—	—	575
					SITE INDEX 75					
20	742	2,227	3,126	3,012	2,480	2,072	1,850	1,722	1,617	1,527
30	483	2,209	3,562	3,598	2,966	2,421	2,136	1,995	1,882	1,783
40	270	1,966	3,673	4,012	3,345	2,671	2,293	2,133	2,017	1,917
50	111	1,653	3,556	4,248	3,674	2,876	2,380	2,175	2,061	1,963
60	1	1,345	3,300	4,305	3,914	3,030	2,421	2,148	2,033	1,941
70	0	1,055	2,915	4,196	4,076	3,193	2,434	2,079	1,947	1,864
80	0	828	2,540	3,998	4,118	3,315	2,452	1,975	1,815	1,740
90	—	645	2,194	3,735	4,093	3,402	2,475	1,869	1,648	1,575
100	—	—	1,900	3,459	3,992	3,380	2,448	1,739	1,451	1,377
110	—	—	—	—	3,832	3,314	2,344	1,600	1,236	1,147
120	—	—	—	—	—	—	2,194	1,389	982	889
130	—	—	—	—	—	—	—	—	711	606
					SITE INDEX 85					
20	1,641	3,542	3,900	3,178	2,554	2,243	2,071	1,932	1,813	1,710
30	1,239	3,704	4,594	3,848	3,008	2,596	2,401	2,249	2,119	2,006
40	876	3,496	4,954	4,356	3,319	2,792	2,570	2,416	2,283	2,167
50	570	3,085	5,020	4,743	3,615	2,906	2,627	2,475	2,344	2,231
60	349	2,626	4,875	5,000	3,872	2,944	2,602	2,451	2,327	2,219
70	173	2,159	4,579	5,127	4,089	3,024	2,526	2,361	2,246	2,147
80	48	1,766	4,202	5,133	4,257	3,058	2,408	2,215	2,112	2,023
90	—	1,429	3,800	5,031	4,343	3,102	2,287	2,025	1,931	1,855
100	—	—	3,418	4,847	4,379	3,089	2,143	1,799	1,710	1,647
110	—	—	—	4,608	4,304	3,016	1,969	1,543	1,454	1,406
120	—	—	—	—	—	2,857	1,738	1,254	1,165	1,133
130	—	—	—	—	—	—	—	936	847	833

changes over the 10-year growth period because average stand diameter increases. The predicted increase in average stand diameter 10 years after the initial thinning is given in table 14 (appendix), by site, age, and the initial residual basal area. Ingrowth and mortality, as well as accretion, affect the change in average stand diameter, and all three elements are incorporated into the program. In our example, average stand diameter would increase from 5.2 to 6.3 inches in 10 years, so the merchantable to total volume ratio would increase from 0.540 to 0.666. Multiplying this ratio by the total cubic-foot volume at age 40 (0.666 x 2,057) gives a merchantable volume of 1,370 cubic feet. Dividing by 80 gives 17.1 cords at age 40, and subtracting the 8.1 cords estimated at age 30 gives the 9.0 cords of growth shown in table 8.

Estimates of board-foot yield (table 9) and board-foot growth for 10 years (table 10) were computed by using the same procedure and the board-foot to total cubic-foot ratios given by equation 5 (appendix).

Many foresters in the central hardwood region are using stocking percent based on Gingrich's *(1964)* tree-area-ratio equation rather than basal area to express stand density. Our computer program calculates both stocking measures, so table 15 (appendix) is included here to aid those interested in expressing growth or yield in relation to stocking percent. The stocking percent shown here by site, age, and residual basal area after the initial thinning will vary when average stand diameter differs from those assumed in table 13 (appendix).

DISCUSSION

The predicted growth and yield values follow expected biological behavior patterns with respect to age, site quality, and stand density. We used these common variables in our equations not only because they are good predictors of growth and yield, but also because they have other utility to silviculturalists and managers and are generally available or else inexpensive and easy to measure.

The equations have received some field testing and it appears that their reliability should be acceptable for most uses. A more complete discussion of sources of error will be included in a Ph.D. manuscript, "Growth and yield functions for thinned upland oak stands," by Martin E. Dale.

The relationships presented here help to establish, in general, the biological capabilities of upland oak stands over a broad range of stand and site conditions. This physical growth-response data are part of the information necessary for objectively evaluating specific thinning practices.

This system of equations indicates that maximum growth in basal area and total cubic-foot volume occurs with a low stocking; usually between 30 and 60 square feet of residual basal area regardless of site or age. Thus the stand density indicated here for maximum growth is somewhat less than that in earlier stocking recommendations *(Dale 1968; Allen and Marquis 1970; and Gingrich 1971)*; however, in such recommendations other factors in addition to growth were considered. Initial thinning to such low densities is usually not recommended because this heavy cutting also tends to increase stem taper, reduce height growth, delay natural pruning, and perhaps stimulate epicormic branching of the residual trees.

If heavy thinning does in fact increase stem taper and reduce height growth, then the values presented here may result in overestimating volume at low stocking, and if adjusted, maximum volume growth would occur at a slightly higher stocking. The basal area and volume growth given here also includes ingrowth trees; and this ingrowth component becomes substantial when thinnings remove 50 percent or more of the original density. With such heavy thinnings, the residual crop trees grow rapidly in diameter, but there are not enough crop trees to fully utilize all available space; hence some of the growth potential of the site is diverted to the smaller understory trees or reproduction.

In general, we feel that in upland oak stands it requires at least 50 percent stocking —based on Gingrich's *(1964)* tree-area ratio equation — to fully occupy the area with potential crop trees, and to prevent extensive development of the understory or advanced reproduction. Also, stocking in excess of 50 percent will reduce the probability of adverse effects on stem taper, height growth, branch development, and natural pruning.

Growth in cordwood and board-foot volume is substantially more on the better sites, although basal-area growth is only slightly affected by site quality. Better sites produce up to 1.3 cords per acre annually between 20 and 30 years while poor sites produce only about ½ cord. Maximum periodic growth rates occur when many trees are reaching ingrowth size; hence the maximum periodic growth rate occurs when mean stand diameter is close to the threshold diameter — 4.6 inches for cordwood and 8.6 inches for sawtimber. Since this threshold diameter is reached at a younger age on the better sites, the peak in periodic mean annual growth is reached sooner on the best sites. This is illustrated in table 8, where cordwood growth on the best sites is shown to be greatest between 20 and 30 years and on poor sites it peaks between 30 and 40 years. Board-foot growth rates (table 10) are greatest at about 50 years on site 85; but on site 55 the peak board-foot growth rate is reached between 70 and 80 years.

Although maximum growth in quantity seems to occur at rather low stocking levels, a variation in basal area of 15 to 20 square feet around this point generally has only a minor effect on the growth rate. For example, on site 65 at age 30, growth is 8 to 9 cords in 10 years with a residual basal area stocking anywhere from 30 to 80 square feet (table 8), and at age 100 we get 4 to 5 cords of growth over the same range of basal-area stocking. Therefore, with such a small loss in quantity of growth and the possibility of adverse effects with low stocking, we feel that in the initial thinning it is better to leave 10 to 20 more square feet of residual basal area than what is indicated for maximum growth rates in the tables.

SUMMARY

Growth and yield equations were developed from the response of 154 permanent growth plots representing a broad range of age, site, and density classes in the upland oak timber type. Originally the stands were fully stocked; but a range of density levels was created by an initial thinning so growth could be studied in relation to stocking. The cubic-foot volume, cordwood, and board-foot volume yields obtained by using these equations are given for a wide range of stand age, site quality, and basal-area classes. Growth was computed for a 10-year period in terms of basal area, cubic-feet, cords, and board feet; and these predictions are given for a broad range of initial age and basal-area classes for site indexes 55, 65, 75, and 85.

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Table 11.—*Regression equations used for growth and yield estimates*

Equation number	Equation form	Mean of dependent variable	Coefficient of determination (R^2)	Root mean square residual ($S_{y \cdot x}$)
(1)	$Y_1 = -BA^{-.8} Ln(B) + 3.68521BA^{-.75} + .011383BSA^{-1.05}$	1.80	0.518	0.733
(2)	$Y_2 = 3.09094 + .00930176S + 1.03909\ Ln(B) - 20.11035A^{-1}$	7.463	.984	.064
(3)	$Y_3 = 1.1341 + .0019876AS$	7.9	.867	1.147
(4)	$Y_4 = -.052676 + .7876045 \cdot \exp[-(1.2987 - .08117D)^{10}]$	.632	.985	.016
(5)	$Y_5 = -.088414 + 3.63827 \cdot \exp[-(2.00 - .125D)^{4}]$	1.277	.969	.235

where

Y_1 = net annual basal area increment per acre including ingrowth for all trees 2.6 inches d.b.h. or larger.

Y_2 = natural logarithm of total cubic foot volume per acre for all trees 2.6 inches d.b.h. or larger, including bark, stump, tip, but no branchwood.

Y_3 = quadratic mean stand diameter of trees 2.6 inches d.b.h. or larger.

Y_4 = ratio of merchantable cubic-foot volume to total cubic-foot volume. Merchantable volume is for all trees 4.6 inches d.b.h. or larger and the volume excludes stump, bark, branches, and tip above 4.5 inch top d.o.b. $Y_4 = 0.0$ if $D<2.3$ and $Y_4 = 0.735$ if $D>16$ inches.

Y_5 = ratio of board-foot volume to total cubic-foot volume. Board-foot volume based on International ¼-inch rule for trees 8.6 inches d.b.h. or larger to a top d.o.b. of 8.5 inches. $Y_5 = 0.0$ if $D<4.8$ inches, and $Y_5 = 3.55$ if $D>16$ inches.

B = basal area in square feet per acre of all living trees 2.6 inches or larger d.b.h.

S = site index in feet at reference age 50.

A = average stand age in years.

D = quadratic mean stand diameter of trees 2.6 inches d.b.h. or larger.

Table 12.—*Ratios of merchantable cubic-foot volume and board-foot volume to total cubic-foot volume, by d.b.h. class*

D.b.h. class (inches)	Merchantable cubic-foot/ total cubic-foot ratio	Board-foot/ total cubic-foot ratio
3	0.0896	0.0
4	.3125	.0
5	.5181	.014
6	.6430	.228
7	.7016	.645
8	.7245	1.250
9	.7322	1.936
10	.7343	2.563
11	.7348	3.035
12	.7349	3.329
13	.7349	3.479
14	.7349	3.536
15	.7349	3.549
16	.7349	3.550
17	.7350	3.550

Table 13.—*Average stand diameter of trees 2.6 inches d.b.h. and larger by site, age, and residual basal area*

[In inches]

Basal area	Average stand age — years: 20	30	40	50	60	70	80	90	100	110
					SITE INDEX 55					
20	3.6	4.8	6.0	7.2	8.4	9.6	10.8	12.0	13.2	14.4
30	3.6	4.8	6.0	7.2	8.3	9.5	10.7	11.9	13.1	14.3
40	3.5	4.7	5.8	7.0	8.2	9.3	10.5	11.6	12.8	13.9
50	3.4	4.5	5.7	6.8	7.9	9.0	10.2	11.3	12.4	13.5
60	3.3	4.4	5.5	6.6	7.7	8.8	9.9	11.0	12.1	13.2
70	3.2	4.3	5.3	6.4	7.4	8.5	9.6	10.6	11.7	12.7
80	—	4.1	5.2	6.2	7.2	8.3	9.3	10.3	11.3	12.4
90	—	—	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
100	—	—	—	—	6.9	7.9	8.8	9.8	10.8	11.8
110	—	—	—	—	—	—	8.7	9.6	10.6	11.6
120	—	—	—	—	—	—	—	—	—	11.4
					SITE INDEX 65					
20	4.1	5.5	6.9	8.3	9.7	11.1	12.5	13.9	15.3	16.8
30	4.0	5.4	6.8	8.2	9.6	11.0	12.4	13.8	15.2	16.6
40	3.9	5.3	6.7	8.0	9.4	10.8	12.2	13.5	14.9	16.3
50	3.8	5.2	6.5	7.8	9.1	10.5	11.8	13.1	14.5	15.8
60	3.7	5.0	6.3	7.6	8.9	10.2	11.5	12.8	14.1	15.3
70	3.6	4.8	6.1	7.4	8.6	9.9	11.1	12.4	13.6	14.9
80	—	4.7	5.9	7.1	8.4	9.6	10.8	12.0	13.2	14.4
90	—	—	5.8	6.9	8.1	9.3	10.5	11.7	12.8	14.0
100	—	—	—	6.8	7.9	9.1	10.3	11.4	12.6	13.7
110	—	—	—	—	—	8.9	10.1	11.2	12.3	13.5
120	—	—	—	—	—	—	—	11.1	12.2	13.3
130	—	—	—	—	—	—	—	—	—	13.2
					SITE INDEX 75					
20	4.5	6.1	7.7	9.4	11.0	12.6	14.3	15.9	17.5	19.1
30	4.5	6.1	7.7	9.3	10.9	12.5	14.2	15.8	17.4	19.0
40	4.4	5.9	7.5	9.1	10.7	12.3	13.8	15.4	17.0	18.6
50	4.2	5.8	7.3	8.8	10.4	11.9	13.4	15.0	16.5	18.0
60	4.1	5.6	7.1	8.6	10.1	11.6	13.1	14.6	16.0	17.5
70	4.0	5.4	6.9	8.3	9.8	11.2	12.6	14.1	15.5	17.0
80	3.9	5.3	6.7	8.1	9.5	10.9	12.3	13.7	15.1	16.5
90	—	5.1	6.5	7.8	9.2	10.6	11.9	13.3	14.7	16.0
100	—	—	6.3	7.7	9.0	10.3	11.7	13.0	14.3	15.7
110	—	—	—	—	8.8	10.2	11.5	12.8	14.1	15.4
120	—	—	—	—	—	—	11.3	12.6	13.9	15.2
130	—	—	—	—	—	—	—	—	13.8	15.1
					SITE INDEX 85					
20	4.9	6.8	8.6	10.5	12.3	14.2	16.0	17.8	19.7	21.5
30	4.9	6.7	8.6	10.4	12.2	14.0	15.9	17.7	19.5	21.4
40	4.8	6.6	8.4	10.2	11.9	13.7	15.5	17.3	19.1	20.9
50	4.6	6.4	8.1	9.9	11.6	13.3	15.1	16.8	18.6	20.3
60	4.5	6.2	7.9	9.6	11.3	13.0	14.6	16.3	18.0	19.7
70	4.4	6.0	7.6	9.3	10.9	12.5	14.2	15.8	17.5	19.1
80	4.2	5.8	7.4	9.0	10.6	12.2	13.8	15.4	16.9	18.5
90	—	5.7	7.2	8.8	10.3	11.8	13.4	14.9	16.5	18.0
100	—	—	7.1	8.6	10.1	11.6	13.1	14.6	16.1	17.6
110	—	—	—	8.4	9.9	11.4	12.9	14.3	15.8	17.3
120	—	—	—	—	—	11.2	12.7	14.2	15.6	17.1
130	—	—	—	—	—	—	—	14.1	15.5	17.0

Table 14.—*Increase in average stand diameter 10 years after thinning, by site, age, and residual basal area*

[In inches]

Residual basal area	Average stand age — years									
	20	30	40	50	60	70	80	90	100	110
				SITE INDEX 55						
20	1.4	1.6	1.6	1.5	1.4	1.3	1.1	0.9	0.7	0.4
30	.9	1.2	1.3	1.2	1.2	1.0	.9	.7	.5	.2
40	.5	.9	1.1	1.1	1.0	.9	.7	.5	.3	.1
50	.2	.8	.9	.9	1.0	.9	.7	.5	.2	.0
60	.0	.6	.8	.9	.8	.8	.6	.5	.3	.0
70	—	.4	.7	.8	.7	.7	.6	.5	.3	.1
80	—	.3	.6	.7	.8	.7	.6	.5	.3	.0
90	—	—	.6	.7	.7	.7	.6	.5	.3	.1
100	—	—	—	—	.6	.6	.6	.5	.3	.1
110	—	—	—	—	—	—	.6	.5	.3	.1
120	—	—	—	—	—	—	—	—	—	.2
				SITE INDEX 65						
20	1.8	2.0	2.1	2.1	2.0	1.8	1.8	1.5	1.2	0.9
30	1.3	1.7	1.8	1.8	1.7	1.5	1.3	1.2	1.0	.7
40	1.0	1.4	1.5	1.5	1.5	1.4	1.3	1.1	.8	.5
50	.6	1.1	1.3	1.4	1.4	1.4	1.2	.9	.8	.5
60	.4	1.0	1.2	1.3	1.3	1.2	1.2	1.0	.7	.5
70	.2	.8	1.1	1.2	1.2	1.1	1.1	.9	.8	.4
80	—	.7	1.0	1.1	1.1	1.1	1.0	.9	.7	.5
90	—	—	.8	1.0	1.1	1.1	1.0	.9	.8	.5
100	—	—	—	.8	1.0	1.0	1.0	.9	.7	.6
110	—	—	—	—	—	.9	.9	.9	.7	.5
120	—	—	—	—	—	—	—	.9	.8	.6
130	—	—	—	—	—	—	—	—	—	.6
				SITE INDEX 75						
20	2.3	2.6	2.7	2.7	2.6	2.6	2.4	2.1	1.9	1.7
30	1.7	2.1	2.3	2.4	2.4	2.3	2.0	1.8	1.6	1.4
40	1.3	1.8	2.0	2.1	2.1	2.1	1.9	1.7	1.5	1.1
50	1.1	1.5	1.8	1.8	1.9	1.9	1.8	1.6	1.4	1.1
60	.8	1.3	1.5	1.7	1.8	1.8	1.7	1.6	1.3	1.0
70	.6	1.2	1.3	1.5	1.5	1.7	1.6	1.4	1.3	1.0
80	.4	1.0	1.1	1.3	1.4	1.5	1.5	1.5	1.3	1.0
90	—	.9	1.0	1.2	1.3	1.3	1.4	1.4	1.3	1.0
100	—	—	1.0	1.0	1.2	1.2	1.2	1.4	1.2	1.1
110	—	—	—	—	1.1	1.1	1.2	1.2	1.2	1.1
120	—	—	—	—	—	—	1.1	1.2	1.1	1.1
130	—	—	—	—	—	—	—	—	1.1	1.1
				SITE INDEX 85						
20	2.9	3.2	3.4	3.5	3.4	3.3	3.3	2.8	2.9	2.4
30	2.2	2.6	2.8	3.0	3.1	3.0	2.9	2.6	2.5	2.1
40	1.7	2.1	2.4	2.6	2.7	2.8	2.8	2.5	2.3	1.9
50	1.4	1.8	2.1	2.2	2.4	2.5	2.6	2.4	2.2	1.9
60	1.2	1.6	1.8	2.0	2.2	2.2	2.3	2.3	2.1	1.9
70	.9	1.3	1.6	1.7	1.9	2.0	2.0	2.1	2.0	1.8
80	.8	1.2	1.4	1.6	1.7	1.8	1.9	1.9	1.9	1.7
90	—	1.0	1.3	1.4	1.6	1.7	1.7	1.8	1.9	1.7
100	—	—	1.1	1.2	1.4	1.5	1.6	1.7	1.7	1.7
110	—	—	—	1.2	1.3	1.4	1.4	1.6	1.6	1.7
120	—	—	—	—	—	1.3	1.4	1.4	1.5	1.6
130	—	—	—	—	—	—	—	1.3	1.4	1.5

Table 15.—*Stocking percent based on tree-area ratio, by site, age, and residual basal area*

Basal area	Average stand age — years									
	20	30	40	50	60	70	80	90	100	110
					SITE INDEX 55					
20	26	23	21	20	19	18	17	17	16	16
30	39	34	32	30	28	27	26	25	24	24
40	53	46	42	40	38	36	35	33	32	32
50	67	59	54	50	48	45	44	42	41	40
60	81	71	65	61	58	55	53	51	50	48
70	96	84	77	72	68	65	62	60	58	57
80	—	98	89	83	78	75	72	70	67	66
90	—	—	101	94	89	85	82	79	77	74
100	—	—	—	—	100	95	92	88	86	83
110	—	—	—	—	—	—	101	98	95	92
120	—	—	—	—	—	—	—	—	—	101
					SITE INDEX 65					
20	25	22	20	19	18	17	16	16	15	15
30	37	33	30	28	27	26	25	24	23	22
40	50	44	40	38	36	34	33	32	31	30
50	63	56	51	48	45	43	42	40	39	38
60	77	68	62	58	55	52	50	49	47	46
70	91	80	73	68	65	62	59	57	56	54
80	—	92	84	79	75	71	68	66	64	62
90	—	—	96	90	85	81	78	75	73	71
100	—	—	—	100	95	91	87	84	82	79
110	—	—	—	—	—	100	96	93	90	88
120	—	—	—	—	—	—	—	102	99	96
130	—	—	—	—	—	—	—	—	—	104
					SITE INDEX 75					
20	24	21	19	18	17	16	16	15	15	14
30	35	31	29	27	26	24	24	23	22	21
40	48	42	39	36	34	33	32	31	30	29
50	60	53	49	46	43	42	40	39	37	36
60	73	65	59	56	53	50	48	47	45	44
70	87	76	70	66	62	59	57	55	53	52
80	101	88	81	76	72	68	66	63	62	60
90	—	100	92	86	81	78	75	72	70	68
100	—	—	103	96	91	87	84	81	78	76
110	—	—	—	—	101	96	92	89	86	84
120	—	—	—	—	—	—	101	98	95	92
130	—	—	—	—	—	—	—	—	103	100
					SITE INDEX 85					
20	23	20	18	17	16	16	15	15	14	14
30	34	30	28	26	25	24	23	22	21	21
40	46	41	37	35	33	32	30	29	29	28
50	58	51	47	44	42	40	38	37	36	35
60	71	62	57	54	51	48	46	45	44	42
70	84	74	67	63	60	57	55	53	51	50
80	97	85	78	73	69	66	63	61	59	58
90	—	97	88	83	78	75	72	69	67	66
100	—	—	99	93	88	84	80	78	75	73
110	—	—	—	102	97	93	89	86	83	81
120	—	—	—	—	—	101	98	94	91	89
130	—	—	—	—	—	—	—	102	99	96

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