PREDICTING GROWTH OF INDIVIDUAL STEMS WITHIN NORTHERN RED OAK SPROUT CLUMPS

Paul S. Johnson and Robert Rogers[1/]

Abstract.--Multiple stems commonly persist for 50 years or longer in clumps of northern red oak (Quercus rubra L.) sprouts originating from stumps. To determine effects of clump density and clump thinning on stump sprout growth, 239 surviving stems within 120 sprout clumps were remeasured 5 years after initial measurement and thinning treatment. Clumps initially ranged from 4 to 22 years old and included eight ages. At the study's initiation, one-third of the clumps were thinned to one stem and one-third to two stems; the remaining clumps contained three or more live stems and were not thinned. Based on 5-year growth of the surviving crop stems, a growth simulation program, COPPICE, was developed for predicting 25th-year diameter, cubic-foot volume, and height of individual stems from initial age, height, d.b.h., relative basal area of the crop stem, and site quality. The model can be used in clump thinning operations as a basis for selecting crop stems with high growth potential or for determining the probable response of any stem to a given initial clump density.

Additional keywords: Quercus rubra L., stump sprouts, coppice, clump thinning, and intermediate cuttings.

Multiple stems commonly persist for 50 years or longer in clumps of northern red oak (Quercus rubra L.) originating from stumps. This characteristic together with a high frequency of sprouting (Johnson 1975, Wendel 1975) may produce basal areas that account for over half a stand's total by age 25 (Johnson 1976). Because of their rapid growth, most of these sprout clumps occupy and maintain dominant crown positions. A potential problem in managing such coppice is maintaining satisfactory quality and growth of individual stems within sprout clumps (Roth and Hepting 1969, Scholz 1948). Nevertheless, it has been estimated that 80 to 90 percent of young northern red oak sprout clumps contain at least one stem of potential crop stem quality (Lamson 1976). Because of this high potential for both stem growth and quality, there is need for an objective basis for selecting crop stems and residual clump densities when thinning clumps. The objective of this study was to develop a growth model for selected crop stems within thinned and unthinned clumps during their first 25 years based on initial clump age, companion stem basal area, crop stem diameter, and site quality.

1/Respectively, Principal Silviculturist and Mensurationist, North Central Forest Experiment Station, USDA Forest Service, Columbia, Missouri.

METHODS

The Study Area

The 127 sprout clumps selected for study were located in eight stands in southwestern Wisconsin in Monroe, Buffalo, LaCrosse, Vernon, and Trempealeau Counties. Stands ranged from 4 to 22 years of age and all originated from clearcutting parent stands 80 to 110 years old.

Soils on the study areas were typic hapludalfs. Textures ranged from sandy loams to silt loams with soil-parent material depth to bedrock ranging from 16 to over 50 inches. Topography varied from nearly level to 55 percent slopes. Site index for red oak on similar sites ranges from about 45 to 70 (Gevorkiantz and Scholz 1948, Einspahr and McComb 1951).

Clump Selection and Thinning

In each stand, 10 to 36 sprout clumps containing three or more live stems were selected and thinned to one or two crop stems, or they were not thinned at all. In unthinned clumps, three stems were identified as crop stems. Approximately equal numbers of clumps were contained in each of the three thinning classes (table 1).

In all sprout clumps selected for study, there were at least three stems that originated at ground line of the parent stump that were in an intermediate-or-greater crown position. One or more of these was selected as a crop stem. In addition, each sprout clump was in a dominant or codominant crown position within the stand as a whole. Crop stems were free of obvious indicators of internal decay, external injury, and abnormal stem form. However, some selected crop stems had forks, sweep, and seams in the lower tree bole.

All stump sprouts and other codominant-or-larger trees were removed by cutting within a specified radius around the center of each study clump (table 2). The resulting "growing spaces" approximated the maximum tree area relation of Gingrich (1967). Removing competition within these radii ensured that each study clump was the primary user of the maximum amount of growing space it could utilize at the time of study establishment.

Measurements

Prior to thinning, initial measurements were made of d.b.h. (0.1 inch) and height (nearest foot) of all living stems within clumps. After five growing seasons, diameters and heights of all living stems were remeasured. The occurrence of epicormic branching in the lower 17 feet of each stem also was observed and recorded at the end of the study period.

Table 1.—Distribution of crop stems[a]

Initial clump age	Clumps sampled	Residual subject stems for thinning levels[b] 1	2	3+	Subject stems per age	Initial d.b.h. Mean	Range	Topographic site coefficient[c] Mean	Range
Years	Number					Inches			
4	18	6	12	18	36	1.0	0.4-1.9	0.57	0.30-0.95
7	18	6	11	18	35	1.2	0.8-1.6	0.39	0.22-0.60
11	17	6	12	16	34	2.5	1.6-4.5	0.58	0.25-1.00
13	17	5	11	18	34	3.0	2.0-4.0	0.61	0.24-0.93
14	5	2	4	3	9	3.9	2.8-4.9	0.65	0.38-0.96
17	14	4	10	15	29	4.9	3.1-7.9	0.67	0.40-0.95
21	13	4	8	15	27	5.4	4.0-6.8	0.55	0.31-1.00
22	18	6	12	17	35	5.2	3.6-6.8	0.69	0.39-0.99
Total	120	39	80	120	239				
Mean						3.2		0.58	

[a] Includes only those stems that survived 5-year study period.
[b] Thinning level 1 = 1 residual stem per clump; 2 = 2 residual stems per clump; 3+ = 3 or more stems per clump (unthinned clumps containing 3 or more live stems).
[c] Values can range from 0.1 to 1.0.

Table 2.--Thinning radius around sprout clumps

Clump age class	Residual stems per clump	Thinning radius
Years	Number	Feet
4-7	1	6
	2	6
	3+[a]	6
11	1	7
	2	8
	3+	8
13-14	1	10
	2	10
	3+	12
17	1	12
	2	14
	3+	15
21-22	1	17
	2	19
	3+	20

[a] Unthinned clumps.

The topographic site coefficient (TSC) was used as a measure of site quality because site indexes of the parent stands were unknown and because site index of young red oak coppice cannot reliably be determined using available curves. Topographic site coefficient is a measure of site quality that integrates the effect of soil depth, slope position, and aspect (Johnson 1975). Values of TSC range from 0.10 (represented by upper southwest-facing slopes with thin soils) to 1.00 (lower northeast-facing slopes with deep soils). To facilitate calculation of TSC, soil-parent material depth (nearest inch) to a maximum of 50 inches was measured near each sprout clump along with slope aspect (degrees azimuth) and slope position (upper, middle, or lower third of slopes).

RESULTS AND DISCUSSION

Crop Stem Survival and Mean Diameter Growth

Of the 254 crop stems in 127 clumps initially selected for study, 94 percent, or 239 stems in 120 clumps, survived the 5-year study period. However, natural mortality among the selected crop stems was only 2.4 percent (6 stems); the remaining losses were man-caused.

Five-year d.b.h. increment of the residual stem in clumps thinned to one stem averaged 2.03 inches (0.41 inches per year); this was 33 percent greater than d.b.h. growth in unthinned clumps which averaged 1.53 inches (0.31 inches per year). Stems in clumps thinned to two stems averaged 1.74 inches in 5-year d.b.h. growth (0.35 inches per year) which was 14 percent greater than the average of unthinned clumps. Gains in 5-year basal area increment relative to unthinned clumps were 49 percent and 24 percent, respectively, for clumps thinned to one and two stems. For a given initial sprout age, mean 5-year d.b.h. increment was highest for 13-year-old sprouts at 2.09 inches (0.42 inches per year). However, mean 5-year basal area increment per crop stem showed a nearly linear increase with stem age, ranging from 0.04 square feet at age 4 to 0.10 square feet at age 21.

A Growth Simulation Model for Individual Stems to Age 25

Because factors other than thinning treatments can affect the growth of individual stems within sprout clumps, we sought a more complete explanation of growth responses. The result was a predictive model for estimating 5-year basal area and volume increments of stems based on regression equations. To simulate longer-term growth, regression solutions were iterated over more than one 5-year period to obtain estimates of future diameters, volumes, and heights of stems. For convenience, we chose 25 years (near our observed upper age limit of 27) as the age for outputting these estimates from any given initial stem age and size, total clump basal area, and site quality.

The model assumes, for a given initial stem d.b.h., initial age, and site quality, that the ratio of basal area of any selected stem to total living clump basal area is the primary determinant of subsequent diameter and volume increment. This ratio was termed relative basal area (RBA) and is a measure of the relative dominance of a stem within a clump. Thus, thinning treatments are not considered in the model, but their effects are imparted through their alteration of RBA. The equations and other features of the simulation model are described below.

Predicting 25th-year diameters.--Data from the 239 surviving crop stems were used to develop an equation for predicting 5-year crop stem basal area increment in square feet ($SBAI_5$). Stepwise linear regression was used to select the "best fit" equation. Because there was substantial correlation among the independent variables in the resulting model, coefficients were recalculated using ridge regression (Rogers and Hilderbrand 1978). This was done to reduce the effects of correlated independent variables which tend to produce regression coefficients that are unstable and too large in absolute value (Marquardt and Snee 1975).

Predictors in the final regression model, used singly or in interactive combination, included initial d.b.h. and age of the crop stem, site quality as reflected by TSC, and RBA. The resulting equation explained 87 percent of the variability in $SBAI_5$, based on the ridge regression adjusted R^2 (equation 1, table 3). Across the range of observed values, estimates of $SBAI_5$ increase as values of the primary variables (i.e., d.b.h., age, RBA, and TSC) increase.

Table 3.--Regression equations used in growth simulation

Equation number	Equation
1	$SBAI_5 = .0119758(DBH) + .044392(RBA) + .0199939(TSC)(RBA) + .25054 \times 10^{-4}(AGE)(DBH)^2 - .1561 \times 10^{-5}(AGE)^2(DBH)^2 + 1.16487 \times 10^{-3}(TSC)(DBH)^2$; $R^2 = .87$[a/]; $Sy \cdot x = .0314$; $p < .01$; $n = 239$.
2	$CBAI_5 = .268738(CBA)^{.5} + .00464055(AGE)(CBA) - .00029973(AGE)^2(CBA) - .138573(CBA)(TSC) + .0211153(CBA/SBA)(TSC)$; $R^2 = .76$[b/]; $Sy \cdot x = .0665$; $p < .01$; $n = 239$.
3	$SVOLI_5 = 8.7300(SBAI_5)^{.9490}\left[(AGE)(DBH)\right]^{.4190}(TSC)^{.10}\left[e^{(-.127127(AGE) + .0039(AGE)^2}\right]$; $R^2 = .96$; $Sy \cdot x = .26$; $p < .01$; $n = 239$[c/]
4	$HEIGHT_0 = 5.12888349\left[(AGE)(DBH)\right]^{.39740885}\left[(TSC)(AGE)\right]^{.11910858}$; $R^2 = .94$; $Sy \cdot x = 3.2$; $p < .01$; $n = 239$[c/].

Where:

$SBAI_5$ = 5-year basal area increment of subject stem in ft^2.
$CBAI_5$ = 5-year basal area increment of companion stems (i.e., all stems except subject stem) in ft^2.
$SVOLI_5$ = 5-year volume increment of subject stem in ft^3.
$HEIGHT_0$ = Initial height of subject stem in ft.
DBH = Initial d.b.h. of subject stem in inches.
AGE = Initial age of subject stem in years.
TSC = Topographic site coefficient.
RBA = Relative basal area of subject stem = (basal area of subject stem)/(total living basal area of sprout clump).
CBA = Basal area of companion stems, i.e., the sum of all stems minus subject stem in ft^2.
SBA = Basal area of subject stem in ft^2.

a/ Ridge regression adjusted R^2; bias added (K) = .08 (Rogers and Hilderbrand 1978).
b/ Ridge regression adjusted R^2; bias added (K) = .09.
c/ Nonlinear model calculated by Marquardt method; in the simulation model, coefficients for $SBAI_5$, AGE·DBH, and TSC in equation 3 vary with age within their respective asymptotic 95 percent confidence intervals.

In order to calculate $SBAI_5$ beyond the first 5-year interval, all subsequent iterations require that RBA (along with age and d.b.h.) be updated to a new initial value. This is necessary because the basal area of all living stems in a clump increases with time, thus potentially changing RBA. To facilitate the calculation of a new RBA, an equation for predicting the 5-year basal area increment of companion stems ($CBAI_5$) (i.e., the basal area of all living stems exclusive of the subject crop stem) was developed. The resulting equation based on ridge regression was a five-variable model that explained 76 percent of the variability in $CBAI_5$ based on the ridge regression adjusted R^2 (equation 2, table 3). For growth periods after the first 5-year interval, calculation of successive RBA's is given below:

$$RBA = \frac{SBA_0 + SBAI_5}{SBA_0 + CBA_0 = SBAI_5 + CBAI_5},$$

where: SBA_0 and CBA_0 are crop stem and companion stem basal areas, respectively, at the end of the preceding 5-year period; $SBAI_5$ and $CBAI_5$ are also for the preceding 5-year period.

Thus, for a given stem, relative basal area does not remain constant, but changes as a function of time and the variables that affect changes in $SBAI_5$ and $CBAI_5$.

Through successive iterations, equations 1 and 2 (table 3) then can be used to predict a future diameter for a sprout stem if its initial age, diameter, and RBA are known, and a value for TSC is known. An interactive computer program, COPPICE (appendix 1), has been written in FORTRAN IV to do this sequence of calculations for initial ages up to 24 years. For initial ages not multiples of five, 25th-year diameters are estimated as a straight-line proportion of the last 5-years' growth to age 25.

Predicting 25th-year volumes and heights.--Data from the surviving crop stems also were used to develop an equation for predicting 5-year crop stem volume increment in cubic feet ($SVOLI_5$). Observed values for individual stem volumes were based on the cubic foot equation of Gevorkiantz and Olsen (1955). A form factor of 0.42 was used for stems 30 feet tall and taller, and a form factor of 0.48 was used for trees 20 feet tall and shorter; for trees between 20 and 30 feet tall, form factor varied between 0.42 and 0.48 in proportion to height. Predictors were selected using linear stepwise regression methods and significance criteria; these included $SBAI_5$, TSC, and initial stem age and d.b.h. The model was then recalculated using nonlinear regression to further improve the fit of the equation to the data. Separate coefficients were used for different age segments of the growth curve based on adjustments within the 95 percent asymptotic confidence limits of the coefficients given in equation 3 (table 3).

In simulating stem volume growth to age 25, iterative solution of the 5-year volume increment equation was used to estimate growth beyond the first 5-year interval as in the diameter growth simulation. However, estimates of volume increment were added to an initial estimate of stem

volume that was calculated from stem basal area, form factor, and height. The initial value for stem height was estimated by nonlinear regression using TSC and stem age and d.b.h. as predictors (R^2 = 0.94) (equation 4, table 3). However, final heights at age 25 were calculated by solving the volume equation of Gevorkiantz and Olsen (1955) for height, using final stem basal area and the appropriate form factor. As in calculating 25th-year diameters, program COPPICE (appendix 1) can be used to calculate 25th-year stem volume and heights given appropriate initial values for stems and site for ages up to 24 years. The components of the simulation model and how the diameter, volume, and height equations interact are shown in figure 1.

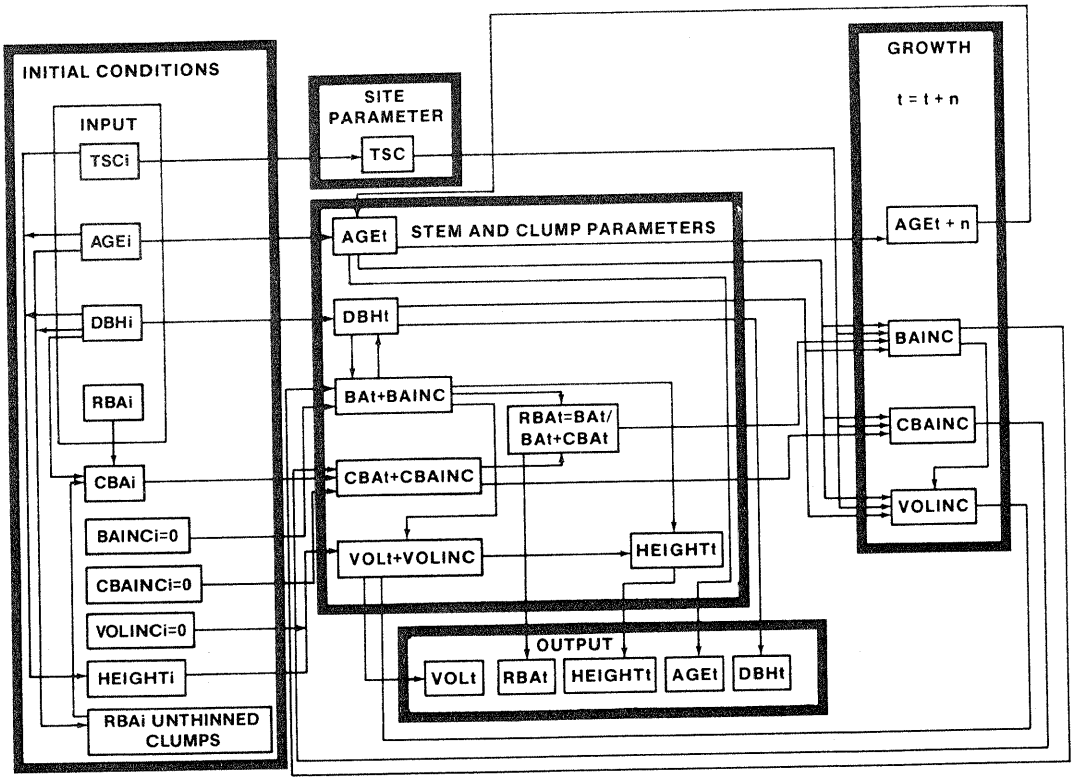

Figure 1.—Diagram of the system used to simulate growth of individual stems in northern red oak sprout clumps. (t = time in years, n = growth interval (5 years), i = initial state, TSC = topographic site coefficient, AGE = clump age, DBH = diameter (inches) at breast height of subject stem, CBA = companion stem basal area, i.e., total clump basal area exclusive of the subject stem, BA = basal area of subject stem, RBA = relative basal area, VOL = gross peeled volume of entire subject stem (cubic feet), BAINC = increase in subject stem basal area over an n-year period, CBAINC = increase in clump basal area exclusive of subject stem over an n-year period, and VOLINC = increase in subject stem volume over an n-year period.)

This model assumes the competitive influences of the adjacent stand remain relatively unchanged after the first 5-year growth period is simulated. Thus, the model may tend to underestimate the growth-depressing effects of encroaching crown closure in subsequent periods, assuming

thinning around each clump is not carried out every 5 years. Departures from estimated values are likely to be greatest where trees of about the same size and vigor as the crop stems occur near the periphery of the initial clump thinning radius. Under these conditions and where clumps are thinned at very young ages, estimates from the simulation model may better represent maximum growth potentials than actual growth.

Application

To facilitate application of program COPPICE and to provide a more convenient overview of stem growth potential, 25th-year estimates are presented in tabular form for a wide range of selected input values of predictors (tables 4-6). Thus, from these tables, effects of different initial stem d.b.h., age, RBA, and site quality on estimates can be evaluated and comparisons then used as criteria for decision making in clump thinning operations and crop stem selection. For specific input values of initial age, diameter, RBA, and site quality not given in tables 4-6, the simulation program can be used (appendix 1).

Examination of tables 4-6 shows that maximum 25th-year diameters and volumes are attained on good sites when initial age is 5, crop stem diameters are relatively large, and there is only one stem per clump (i.e., RBA = 1). Thus, if both growth and quality of individual stems is a silvicultural objective, young clumps could be thinned to the largest stem of potentially high quality. To aid the user in defining relative stem size (e.g., large, medium, small) for a given age, the relation between d.b.h. of the dominant stem and stem age in unthinned clumps is presented in figure 2. In addition, values for initial d.b.h. in tables 4-6 represent the approximate range of observed values; thus, the largest initial d.b.h. tabulated for a given age will be close to the maximum observed.

By inspection of tables 4-6, the effect of thinning at a given age to a RBA of 1.0 (i.e., one stem) or to a RBA of 0.5 can be compared to expected growth of the same stem in average unthinned clumps. For example, on good sites (TSC = 1.0), a clump thinned to one 1-inch stem at age five can be expected to produce a tree 10.8 inches d.b.h. at age 25; in contrast, the same stem in an unthinned clump would be expected to be 4.3 inches smaller, or 6.5 inches d.b.h. The same crop stem with an initial RBA of 0.5 would be expected to reach 8.8 inches d.b.h. at age 25. Numerous other comparisons also can be made using tables 4-6, including the effects of site quality and stem age and d.b.h. at time of thinning.

Because estimates for stems in unthinned clumps in tables 4-6 are based on the mean trend of RBA in such clumps, these estimates are useful for projecting average gains in thinning to a specific RBA in comparison to average unthinned clumps. However, because of variability in natural thinning rates in unthinned clumps, number of individual stems per clump may vary widely; thus, actual RBAs of individual stems in unthinned clumps will vary accordingly. For exceptionally large stems in unthinned clumps (i.e., those considerably larger than the mean diameter of dominants), comparison with the same stem in a clump thinned to one stem will indicate that such a stem will respond little to thinning. This occurs because the model assumes that such large stems account for most of the clump basal area and, thus, they would grow essentially as single-stem clumps.

Table 4.--Estimates of 25th-year diameter (inches), height (feet), and volume (cubic feet)a/ for sprout stems on good sites (TSC = 1.0)

GOOD SITE (TOPOGRAPHIC SITE COEFFICIENT= 1.000)

INITIAL RELATIVE BASAL AREA=1.00

	INITIAL AGE (YEARS)											
	5			10			15			20		
INITIAL DBH	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL
0.5	10.6	65.8	16.9									
1.0	10.8	66.8	18.0	8.5	60.1	9.9						
1.5	11.2	67.8	19.4	8.8	61.8	10.9	6.5	53.2	5.2	4.2	40.4	1.6
2.0	11.6	68.7	21.0	9.1	63.2	12.1	6.9	55.4	6.0	4.6	44.7	2.1
2.5	12.0	69.6	22.9	9.5	64.5	13.5	7.2	57.3	6.9	5.0	48.1	2.7
3.0				10.0	65.8	15.0	7.7	59.0	7.9	5.4	50.9	3.4
3.5				10.5	66.9	16.8	8.1	60.7	9.1	5.8	53.3	4.2
4.0				10.9	68.0	18.7	8.6	62.1	10.5	6.3	55.4	5.0
4.5							9.1	63.5	11.9	6.8	57.2	6.0
5.0							9.6	64.8	13.5	7.2	58.9	7.1
5.5							10.1	66.1	15.3	7.7	60.5	8.3
6.0										8.2	62.0	9.6
6.5										8.7	63.4	11.1
7.0										9.2	64.8	12.7
7.5										9.8	66.1	14.4
8.0										10.3	67.3	16.3
8.5										10.8	68.6	18.3
9.0										11.3	69.7	20.5

INITIAL RELATIVE BASAL AREA=0.50

	INITIAL AGE (YEARS)											
	5			10			15			20		
INITIAL DBH	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL
0.5	8.5	61.3	10.1									
1.0	8.8	62.4	11.0	6.3	56.1	5.9						
1.5	9.2	63.5	12.3	7.2	58.0	6.8	5.3	50.4	3.2	3.4	40.4	1.1
2.0	9.7	64.7	13.9	7.6	59.7	8.0	5.7	52.8	3.9	3.9	44.3	1.5
2.5	10.2	65.9	15.8	8.1	61.2	9.3	6.2	54.6	4.8	4.3	47.4	2.0
3.0				8.7	62.7	10.8	6.7	56.7	5.8	4.8	50.0	2.7
3.5				9.2	64.0	12.5	7.2	58.4	6.9	5.3	52.3	3.4
4.0				9.8	65.2	14.3	7.7	60.0	8.2	5.8	54.3	4.2
4.5							8.3	61.5	9.6	6.3	56.1	5.1
5.0							8.8	62.9	11.2	6.8	57.8	6.2
5.5							9.4	64.2	12.9	7.3	59.4	7.4
6.0										7.9	61.0	8.7
6.5										8.4	62.4	10.1
7.0										8.9	63.8	11.6
7.5										9.5	65.2	13.3
8.0										10.0	66.5	15.2
8.5										10.5	67.7	17.2
9.0										11.1	68.9	19.3

INITIAL RELATIVE BASAL AREA FOR MEAN TREND OF UNTHINNED CLUMPS

	INITIAL AGE (YEARS)																	
	5			b/	10				15				20			
INITIAL DBH	DBH	HT	VOL	PBA	DBH	HT	VOL	PBA	DBH	HT	VOL	PBA	DBH	HT	VOL	PBA
0.5	4.7	50.0	2.5	0.04												
1.0	8.5	56.4	5.5	0.15	4.4	48.9	2.2	0.06								
1.5	8.4	61.8	9.8	0.33	5.8	53.5	3.8	0.14	3.8	46.1	1.5	0.06	2.5	39.3	0.8	0.02
2.0	10.0	65.4	15.1	0.54	6.7	57.2	5.9	0.25	4.8	49.6	2.4	0.10	3.1	42.8	0.9	0.04
2.5	11.6	68.6	21.0	0.92	7.8	60.4	8.4	0.39	5.3	52.4	3.4	0.16	3.7	45.9	1.4	0.07
3.0					8.8	63.0	11.2	0.56	6.1	55.0	4.7	0.23	4.3	48.8	2.1	0.10
3.5					9.8	65.4	14.4	0.79	6.8	57.4	6.2	0.32	4.9	51.0	2.8	0.15
4.0					10.9	67.8	18.4	0.99	7.6	59.6	7.8	0.42	5.5	53.2	3.6	0.18
4.5									8.3	61.6	9.7	0.53	6.1	55.3	4.6	0.22
5.0									9.0	63.5	11.9	0.65	6.8	57.2	5.8	0.27
5.5									9.6	65.3	14.2	0.79	7.2	59.0	7.0	0.33
6.0													7.8	60.7	8.4	0.40
6.5													8.4	62.3	10.0	0.48
7.0													8.9	63.9	11.7	0.54
7.5													9.5	65.4	13.6	0.62
8.0													10.1	66.8	15.6	0.70
8.5													10.7	68.2	17.8	0.79
9.0													11.3	69.6	20.2	0.89

a/ Gross peeled volume in cubic feet for entire stem.

b/ RBA = estimated relative basal area of the crop stem in unthinned clumps at the given initial age.

Table 5.--Estimates of 25th-year diameter (inches), height (feet), and volume (cubic feet)[a] for sprout stems on medium sites (TSC = 0.55)

MEDIUM SITE (TOPOGRAPHIC SITE COEFFICIENT= 0.550)

INITIAL RELATIVE BASAL AREA=1.00

	INITIAL AGE (YEARS)											
	5			10			15			20		
INITIAL DBH	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL
0.5	9.4	59.2	12.0									
1.0	9.7	60.2	12.8	7.7	54.8	7.4						
1.5	10.0	61.0	13.6	8.0	56.3	8.2	6.0	49.1	4.1	4.0	38.2	1.4
2.0	10.3	61.7	15.0	8.3	57.6	9.1	6.4	51.2	4.8	4.4	42.0	1.8
2.5	10.7	62.4	16.3	8.7	58.8	10.2	6.7	52.9	5.5	4.7	45.1	2.3
3.0				9.1	59.9	11.3	7.1	54.4	6.3	5.2	47.5	2.9
3.5				9.5	60.8	12.6	7.6	55.7	7.3	5.6	49.6	3.6
4.0				10.0	61.7	14.0	8.0	57.0	8.3	6.0	51.5	4.3
4.5							8.4	58.2	9.5	6.5	53.1	5.1
5.0							8.9	59.3	10.8	7.0	54.6	6.1
5.5							9.4	60.3	12.2	7.4	56.0	7.1
6.0										7.9	57.3	8.2
6.5										8.4	58.5	9.5
7.0										8.9	59.7	10.8
7.5										9.4	60.6	12.3
8.0										9.9	61.9	13.9
8.5										10.4	63.0	15.6
9.0										10.9	64.0	17.4

INITIAL RELATIVE BASAL AREA=0.50

	INITIAL AGE (YEARS)											
	5			10			15			20		
INITIAL DBH	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL
0.5	7.7	55.7	7.6									
1.0	8.0	56.5	8.2	6.3	51.4	4.6						
1.5	8.3	57.4	9.0	6.6	53.0	5.3	5.0	46.7	2.6	3.3	38.1	0.9
2.0	8.7	58.3	10.1	7.0	54.5	6.1	5.4	48.9	3.2	3.7	41.5	1.3
2.5	9.2	59.2	11.4	7.4	55.9	7.1	5.8	50.7	3.9	4.2	44.2	1.8
3.0				7.9	57.1	8.2	6.3	52.2	4.7	4.6	46.5	2.3
3.5				8.4	58.1	9.4	6.7	53.6	5.6	5.1	48.5	2.9
4.0				8.9	59.1	10.8	7.2	55.0	6.6	5.6	50.3	3.6
4.5							7.7	56.2	7.7	6.1	51.9	4.4
5.0							8.2	57.4	8.9	6.6	53.4	5.3
5.5							8.6	58.5	10.3	7.1	54.9	6.3
6.0										7.6	56.2	7.4
6.5										8.1	57.5	8.6
7.0										8.6	58.7	10.0
7.5										9.1	59.9	11.4
8.0										9.6	61.0	13.0
8.5										10.1	62.1	14.6
9.0										10.7	63.2	16.4

INITIAL RELATIVE BASAL AREA FOR MEAN TREND OF UNTHINNED CLUMPS

	INITIAL AGE (YEARS)																			
	5			b/	10				15				20			
INITIAL DBH	DBH	HT	VOL	RBA	DBH	HT	VOL	RBA	DBH	HT	VOL	RBA	DBH	HT	VOL	RBA
0.5	4.4	46.2	2.1	0.04												
1.0	6.1	51.8	4.4	0.15	4.2	45.3	1.9	0.06								
1.5	7.6	55.9	7.4	0.33	5.3	49.5	3.1	0.14	3.6	43.0	1.3	0.06	2.5	37.0	0.5	0.02
2.0	9.0	58.9	10.9	0.59	6.2	52.5	4.7	0.25	4.4	46.1	2.0	0.10	3.0	40.0	0.8	0.04
2.5	10.3	61.5	14.9	0.92	7.2	55.1	6.5	0.39	5.1	48.5	2.9	0.16	3.6	42.7	1.3	0.07
3.0					8.1	57.4	8.5	0.56	5.8	50.6	3.8	0.23	4.2	45.1	1.8	0.10
3.5					8.9	59.4	10.9	0.76	6.4	52.7	5.0	0.32	4.7	47.3	2.4	0.13
4.0					9.9	61.5	13.8	0.99	7.1	54.9	6.3	0.42	5.3	49.3	3.2	0.18
4.5									7.8	56.3	7.6	0.53	5.9	51.1	4.0	0.22
5.0									8.4	58.0	9.5	0.65	6.4	52.8	5.0	0.27
5.5									9.1	59.5	11.3	0.79	7.0	54.4	6.1	0.33
6.0													7.5	55.9	7.3	0.40
6.5													8.1	57.4	8.6	0.48
7.0													8.6	58.8	10.0	0.54
7.5													9.2	60.1	11.6	0.62
8.0													9.7	61.4	13.3	0.70
8.5													10.3	62.7	15.2	0.79
9.0													10.8	63.9	17.2	0.89

a/ Gross peeled volume in cubic feet for entire stem.

b/ RBA = estimated relative basal area of the crop stem in unthinned clumps at the given initial age.

Table 6.--Estimates of 25th-year diameter (inches), height (feet), and volume (cubic feet)[a] for sprout stems on poor sites (TSC = 0.10)

POOR SITE (TOPOGRAPHIC SITE COEFFICIENT= 0.100)

INITIAL RELATIVE BASAL AREA=1.00

	INITIAL AGE (YEARS)											
	5			10			15			20		
INITIAL DBH	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL
0.5	6.3	47.5	7.5									
1.0	8.5	48.3	8.0	6.9	44.5	4.9						
1.5	8.8	48.9	8.7	7.2	45.7	5.4	5.6	40.5	2.9	3.7	32.3	1.0
2.0	9.1	49.4	9.4	7.5	46.8	6.1	5.9	42.2	3.3	4.1	35.6	1.4
2.5	9.4	49.8	10.1	7.9	47.8	6.8	6.2	43.7	3.9	4.5	37.9	1.8
3.0				8.2	48.8	7.5	6.6	44.9	4.5	4.9	39.8	2.2
3.5				8.6	49.4	8.4	7.0	45.9	5.2	5.3	41.0	2.7
4.0				9.0	50.0	9.3	7.4	46.8	5.9	5.8	42.3	3.2
4.5							7.8	47.5	6.7	6.2	43.5	3.9
5.0							8.3	48.0	7.5	6.7	44.6	4.5
5.5							8.7	48.7	8.5	7.1	45.7	5.3
6.0										7.6	46.6	6.2
6.5										8.1	47.5	7.1
7.0										8.5	48.4	8.1
7.5										9.0	49.2	9.2
8.0										9.5	50.0	10.3
8.5										10.0	50.8	11.6
9.0										10.4	51.6	12.9

INITIAL RELATIVE BASAL AREA=0.50

	INITIAL AGE (YEARS)											
	5			10			15			20		
INITIAL DBH	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL	DBH	HT	VOL
0.5	7.1	45.3	5.2									
1.0	7.2	45.7	5.4	5.8	42.1	3.2						
1.5	7.4	46.3	5.8	6.0	43.3	3.8	4.6	38.7	1.9	3.1	32.2	0.7
2.0	7.7	46.8	6.4	6.4	44.4	4.2	5.0	40.5	2.3	3.6	35.1	1.0
2.5	8.1	47.3	7.2	6.8	45.4	4.8	5.4	42.0	2.8	4.0	37.2	1.4
3.0				7.2	46.4	5.5	5.8	43.2	3.4	4.5	38.7	1.8
3.5				7.6	47.1	6.3	6.3	44.2	4.0	4.9	39.9	2.2
4.0				8.1	47.8	7.2	6.7	45.0	4.7	5.4	41.2	2.7
4.5							7.2	45.7	5.4	5.9	42.4	3.3
5.0							7.7	46.3	6.3	6.3	43.6	4.0
5.5							8.2	47.1	7.2	6.8	44.6	4.8
6.0										7.3	45.6	5.6
6.5										7.8	46.6	6.5
7.0										8.3	47.5	7.5
7.5										8.8	48.3	8.5
8.0										9.3	49.2	9.7
8.5										9.8	50.0	10.9
9.0										10.2	50.8	12.2

INITIAL RELATIVE BASAL AREA FOR MEAN TREND OF UNTHINNED CLUMPS

	INITIAL AGE (YEARS)															
	5			b/	10				15				20			
INITIAL DBH	DBH	HT	VOL	RBA	DBH	HT	VOL	RBA	DBH	HT	VOL	RBA	DBH	HT	VOL	RBA
0.5	4.4	38.8	1.7	0.04												
1.0	5.8	42.7	3.2	0.15	4.1	37.7	1.4	0.06								
1.5	6.9	45.2	4.9	0.33	4.9	40.6	2.3	0.14	3.5	35.9	1.0	0.06	2.4	31.4	0.4	0.02
2.0	8.0	47.2	6.9	0.59	5.8	42.9	3.3	0.25	4.2	38.4	1.5	0.10	3.0	33.9	0.7	0.04
2.5	9.0	49.0	9.2	0.92	6.5	44.9	4.4	0.39	4.8	40.4	2.1	0.16	3.5	35.9	1.0	0.07
3.0					7.3	46.6	5.7	0.56	5.4	42.0	2.8	0.23	4.1	37.4	1.4	0.10
3.5					8.1	48.1	7.2	0.76	6.0	43.4	3.6	0.32	4.6	38.8	1.9	0.13
4.0					8.9	49.8	9.1	0.99	6.6	44.7	4.5	0.42	5.1	40.3	2.4	0.18
4.5									7.2	45.8	5.5	0.53	5.7	41.7	3.1	0.22
5.0									7.8	46.8	6.6	0.65	6.2	43.0	3.8	0.27
5.5									8.5	48.0	7.9	0.79	6.7	44.2	4.6	0.33
6.0													7.2	45.4	5.5	0.40
6.5													7.8	46.5	6.4	0.46
7.0													8.3	47.5	7.5	0.54
7.5													8.8	48.6	8.7	0.62
8.0													9.4	49.5	9.9	0.70
8.5													9.9	50.5	11.3	0.79
9.0													10.4	51.4	12.7	0.89

a/ Gross peeled volume in cubic feet for entire stem.

b/ RBA = estimated relative basal area of the crop stem in unthinned clumps at the given initial age.

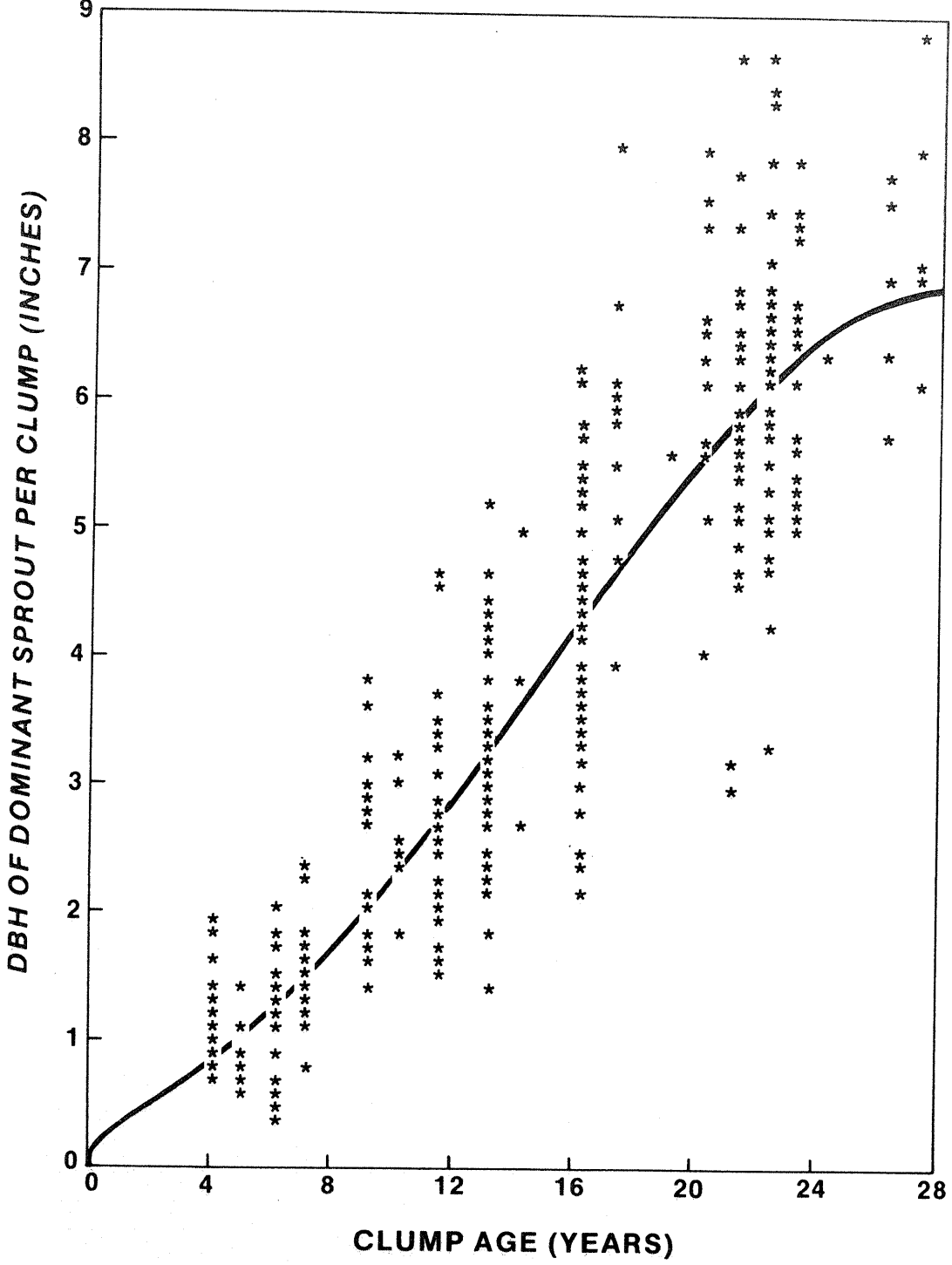

Figure 2.--D.b.h. of dominant sprout per clump in unthinned clumps. ($D.b.h._{in} = 0.3292\ (AGE)^{0.5} + 0.007860(AGE)^{2.5} - 0.001250(AGE)^{3}$; $R^2 = 0.96$; $Sy{\cdot}x = 0.89$; $p < 0.01$; $n = 399$; each data point represents 1 to 8 observations.)

If values of TSC are not available, TSC can be estimated from average height/d.b.h. relations for specific tree ages, based on equation 4 in table 3. Topographic site coefficient curves derived from this relation are given for tree ages 5, 10, 15, and 20 years (fig. 3). Because TSC was derived from relations between soil and topographic factors and sprout height in southern Wisconsin and southern Minnesota, its applicability elsewhere is unknown. Where the pattern of sprout height growth differs greatly from that on which TSC originally was based, neither direct calculation of TSC from soil and topographic factors nor indirect estimation from equation 4 in table 3 (or fig. 3) may yield a reliable estimate of site quality.

The functional relation between TSC and available site index curves also is unknown, although the TSC range (0.1 to 1.0) approximates the site index range of 40 to 70 for the site index curves of Gevorkiantz (1957). Furthermore, direct calculation of site index from height/age relations of red oak stump sprouts is not appropriate because this relation is markedly different from that assumed in available site index curves (Johnson 1975).

Field procedures for selecting crop stems in sprout clumps also should consider stem quality. A practical guide for selecting crop stems 3.5 inches d.b.h. and larger is available (Sonderman 1979), and could be used to complement tables 4-6. Because changes in stem form in red oaks less than 3 inches d.b.h. occur rapidly and usually for the better (Wendel 1975), stem quality evaluation in stands less than about 14 years of age may be unnecessary or impossible. However, early clump thinning should improve stem quality by reducing stem sweep, i.e., the curvature often common in stems on the periphery of clumps caused by their bending away from the clump center.

Although red oak has been classified as a potentially prolific producer of epicormic branches (Trimble and Seegrist 1973), we observed relatively little serious epicormic branching on stems in either thinned or unthinned clumps in the present study. Most of the epicormic branches that did appear occurred in clumps 17 years of age or older, and of these branches, most did not survive the 5-year study period. Exceptions appeared not to be related to thinning intensity or stem crown class, but to the prethinning occurrence of such branches. Thus, it is recommended that crop stems be selected from among those showing little or no prior history of epicormic branch development, as suggested by Ward (1966). Where epicormic branching is associated with entire clumps, such clumps could be bypassed in clump thinning operations.

CONCLUSIONS

The growth model described can be used to estimate probable 25th-year diameters, heights, and volumes of individual stems in young red oak sprout clumps. The model indicates that diameters and volumes of individual sprout stems can be substantially increased by clump thinning; specific gains will depend on crop stem diameter, age, and relative basal area at time of thinning, and site quality. It thus provides the silviculturist with an objective basis for selecting crop stems when thinning young clumps. For trees 3.5 inches d.b.h. and larger, the model also can be used in conjunction with an available guide for evaluating stem quality.

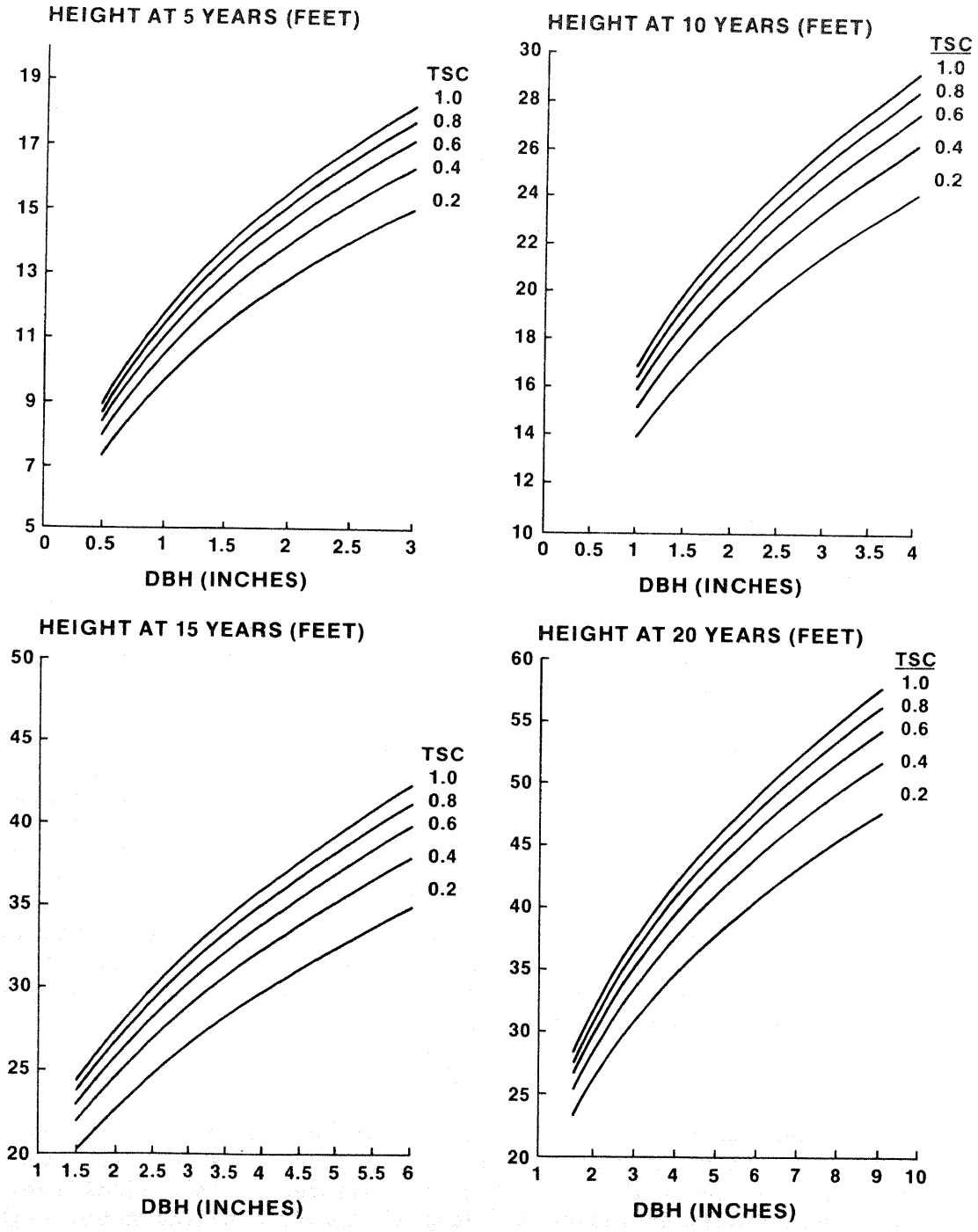

Figure 3.--Height of sprouts in unthinned clumps in relation to d.b.h., clump age, and site quality (topographic site coefficient (TSC)). (Based on equation 4, table 3.)

Primary limitations to application of the model include (1) a quantitative site quality expression whose efficacy is unknown outside the study region, and (2) an unmeasured effect of increasing crown closure and stand stocking beyond the first 5-year growth period. The model nevertheless provides a reasonable expression of the growth potential of individual stems within sprout clumps for a given initial age, d.b.h., relative stem basal area, and site quality.

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