GROWTH AND YIELD PREDICTION

BASED ON

THE PMRC SLASH PINE THINNING STUDY

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During the past 30 years over five million acres of slash pine (*Pinus elliottii* Engelm.) plantations have been planted in the lower coastal plain of South Carolina, Georgia and Florida (Bechtold and Ruark, 1988). Most of these plantations were established following the harvest of an existing natural stand and some form of mechanical site preparation. In this region where pulpwood production predominates, the role of thinning in the management of these plantations has received little attention.

During the period 1964 through 1970, Union Camp Corporation and St. Regis Paper Company established a number of experimental installations designed to study the relationship between tree growth and growing space and between growth response and thinning intensity. In 1977 these companies made their installations available to the Plantation Management Research Cooperative (PMRC) of the School of Forest Resources of the University of Georgia for imposition of the thinning treatments, subsequent measurements, and analysis.

Description of the Study

In 1978 the PMRC funded a field crew to perform the thinnings and collect data at 22 installations, and again in 1980 when an additional 7 installations became a part of the project. The counties and states in which these 29 installations are located are listed in Table 1, as are the thinning ages, last remeasurement ages, and average site indices.

Each installation consists of a set of monumented plots which had been established in 2- and 3-year-old mechanically site-prepared plantations at a location with reasonably homogeneous site conditions. Based on soil profile

Table 1. Location of the 29 installations by county and state, with thinning age, remeasurement age and average site index.

Install. No.	County	State	Thinning Age (1978 & 1980)	Remeas. Age (1988)	Av. Site Index*
2	Beaufort	SC	15.7	25.6	65
5	Tattnall	GA	14.7	24.7	59
6	Evans	GA	15.8	25.7	61
7	McIntosh	GA	14.8	24.7	60
9	Charlton	GA	14.8	24.7	59
10	Charlton	GA	14.8	23.7	65
11	Charlton	GA	16.8	26.7	59
12	Camden	GA	14.8	24.8	73
13	Clinch	GA	14.9	24.9	60
14	Ware	GA	16.9	26.8	64
15	Volusia	FL	14.9	24.8	58
16	Nassau	FL	11.9	21.8	55
17	Nassau	FL	9.9	19.8	65
18	Nassau	FL	10.9	20.8	58
19	Echols	GA	12.9	22.9	61
20	Madison	FL	13.9	23.8	53
21	Echols	GA	12.9	22.9	63
22	Clinch	GA	9.9	19.9	64
23	Flagler	FL	10.9	20.9	50
25	Madison	FL	12.9	22.8	52
26	Lafayette	FL	10.9	20.8	61
27	Madison	FL	12.9	22.8	48
28	Santa Rosa	FL	13.9	21.9	49
29	Santa Rosa	FL	12.9	20.9	56
30	Santa Rosa	FL	14.9	22.9	60
31	Santa Rosa	FL	12.9	20.9	60
32	Escambia	FL	13.9	21.9	63
33	Santa Rosa	FL	13.9	21.9	63
34	Okaloosa	FL	13.9	21.9	61

*Site index based on 1988 measurement and equation(3) descriptions, soil drainage classes varied from very poorly to somewhat excessively drained. Mechanical site preparation included burning and bedding, disking with and without bedding, and single or double chopping with and without bedding.

Two types of plots were installed at each location: basic subseries (BS) plots and suppression and release (SAR) plots. Original planting survival densities and nominal thinnings imposed at each location are summarized in Table 2.

BS plots at each location represent planting survival densities of 100, 200, 300, 450, 700, and at some locations, 900 trees per acre as evenly spaced as possible. These plots have remained unthinned for the duration of the study. Measurement plots within the BS plots originally contained 25 trees with plot sizes varying accordingly. On each of the 150 BS plots surviving trees were measured for dbh and total height, and the number of trees per acre surviving was calculated. For example, for a 700 BS plot with 20 trees surviving, the trees per acre is (20/25) x 700 = 560.

SAR plots were all 1/4-acre plots. They were intended to represent the same initial stocking levels as the BS plots, and to accommodate the thinning treatments. On each of 207 SAR plots a 1/10-acre measurement plot was established and the whole plot marked for thinning. Thinning was selective from below, aimed at uniform distribution of desirable remaining trees. Thinning intensities were determined by the surviving trees per acre of the BS plots of successively lower nominal stockings. For example, if there were 3 SAR plots with nominal stockings of 700 per acre, one was thinned to the same trees per acre currently surviving in the 450 BS plot, another to match the current survival in the 300 BS plot, and the third to match the current survival in the 200 BS plot. Thinning intensities were randomly assigned to

Table 2. Summary of original planting survival densities and nominal thinning intensities at each location. The symbol x denotes representation in the data.

Install. No.	Planting survival density						Planting survival density - Nominal density thinned to													
2	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
5	x	x	x	x	x	x	-	x	x	-	x	x	-	x	x	x	x	x	x	x
6	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
7	x	x	x	x	x	x	-	x	x	-	x	x	x	x	x	-	-	-	x	x
9	x	x	x	x	x	-	-	x	x	-	x	x	-	x	x	-	-	-	-	-
10	x	x	x	x	x	-	-	x	x	-	x	x	-	x	x	-	-	-	-	-
11	x	x	x	x	x	-	-	x	x	-	x	x	-	x	x	-	-	-	-	-
12	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
13	x	x	x	x	x	x	-	x	x	-	x	x	-	-	-	-	-	-	-	x
14	x	x	x	x	x	-	-	x	x	x	x	x	-	x	-	-	-	-	-	-
15	-	-	-	-	x	-	-	-	-	-	-	-	-	x	x	-	-	-	-	-
16	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
17	x	x	x	x	x	-	x	x	x	-	x	x	-	-	x	-	-	-	-	-
18	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
19	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
20	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
21	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
22	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
23	x	x	x	x	x	-	x	x	x	-	x	x	-	-	-	-	-	-	-	-
25	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
26	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
27	x	x	x	x	x	-	x	x	x	-	x	x	-	-	x	-	-	-	-	-
28	x	x	x	x	x	-	x	x	x	-	x	x	-	-	-	-	-	-	-	-
29	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
30	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
31	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
32	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-
33	x	x	x	x	x	-	x	x	x	-	x	x	-	-	-	-	-	-	-	-
34	x	x	x	x	x	-	x	x	x	-	x	x	x	x	x	-	-	-	-	-

plots. All remaining trees on the 1/10-acre measurement plots were measured for dbh and total height. Cut trees were measured for dbh only.

BS and SAR plots were remeasured on a 2-year cycle, the last in 1988. Age at thinning varied from 10 to 17 years. Average site index for the 29 locations varied from 48 to 73 (index age 25, and based on the last remeasurement).

Survival Prediction

Survival data for the BS plots from age 2 or 3 when the plots were installed to the age when the thinnings were made, and for both the BS and SAR plots, from the thinning age to the 1988 remeasurement age, were used to estimate the parameters in a survival prediction equation.

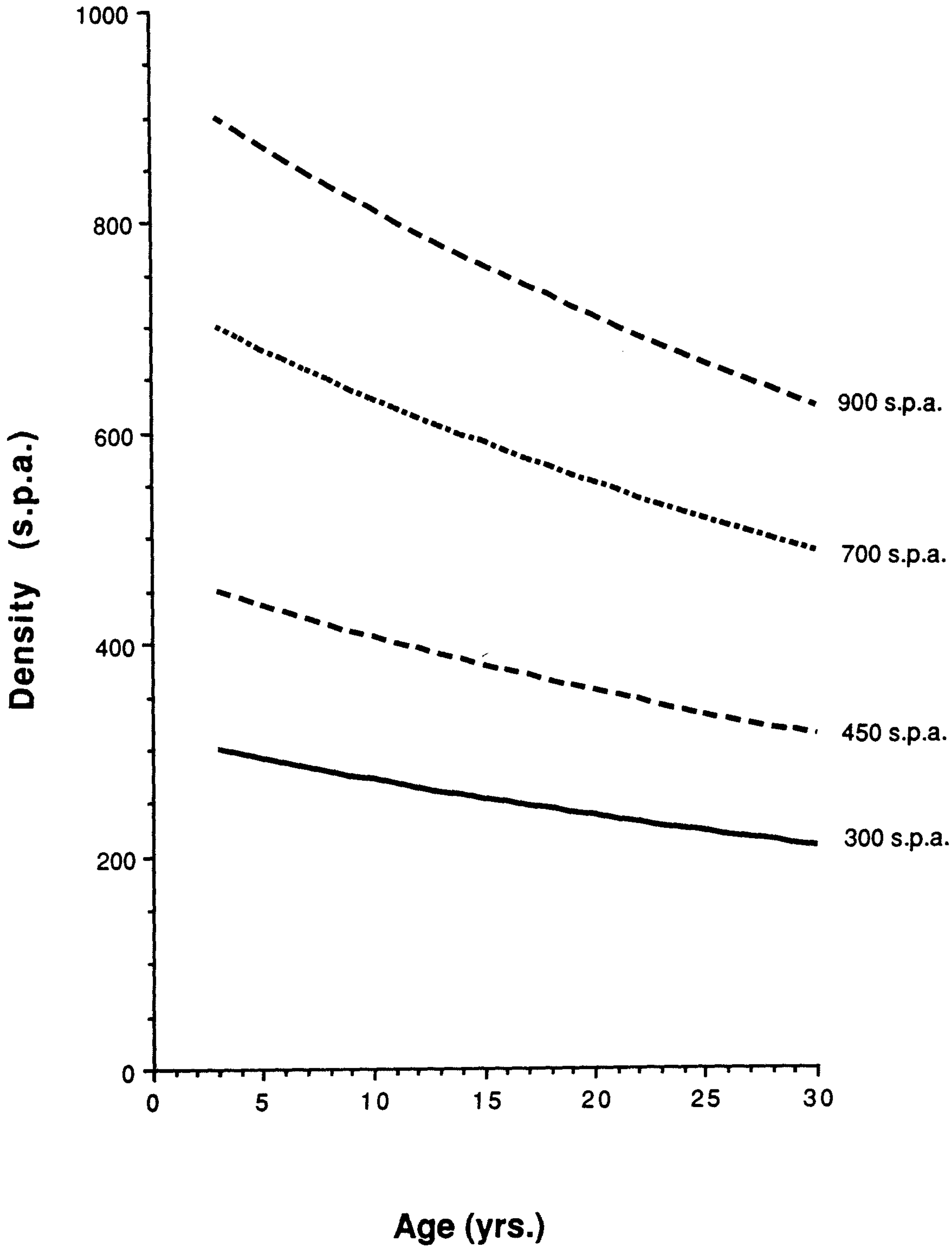
$$N_2 = N_1 \exp\{-0.1524\ [(A_2/10)^{0.9156} - (A_1/10)^{0.9156}]\} \qquad (1)$$

$$n = 507 \qquad R^2 = 0.94 \qquad S_{y.x} = 43$$

where N_1 and N_2 are the numbers of surviving trees per acre at ages A_1 and A_2, respectively. Parameter estimates for the SAR plots did not differ significantly from those for the BS plots. Perhaps unexpectedly, this means, for example, that a plantation that was thinned to 300 trees per acre at age 15 and an unthinned plantation with 300 trees per acre at age 15, experienced essentially the same survival to age 25.

Equation (1) was used to generate the survival curves shown in Figure 1 for planting survival densities of 300, 450, 700 and 900 trees per acre from age 3 to age 30.

Figure 1. Survival curves for four different planting survival densities.



Dominant/Codominant Height Projection

The average height of all trees classified as dominant or codominant was calculated for each BS and SAR plot at the thinning age and at the 1988 measurement. A height projection equation was fitted to the data.

$$H_2 = H_1 \{[1 - \exp(-0.0456\ A_2)]/[1 - \exp(-0.0456\ A_1)]\}^{1.1830} \tag{2}$$

$$n = 357 \qquad R^2 = 0.62 \qquad S_{y.x} = 7\%\ \text{of predicted}\ H$$

where H_1 and H_2 are the average dominant/codominant heights at ages A_1 and A_2, respectively. The implied anamorphic site index equation with an index age of 25 years is

$$H = 1.5776\ S[1 - \exp(-0.0456\ A)]^{1.1830} \tag{3}$$

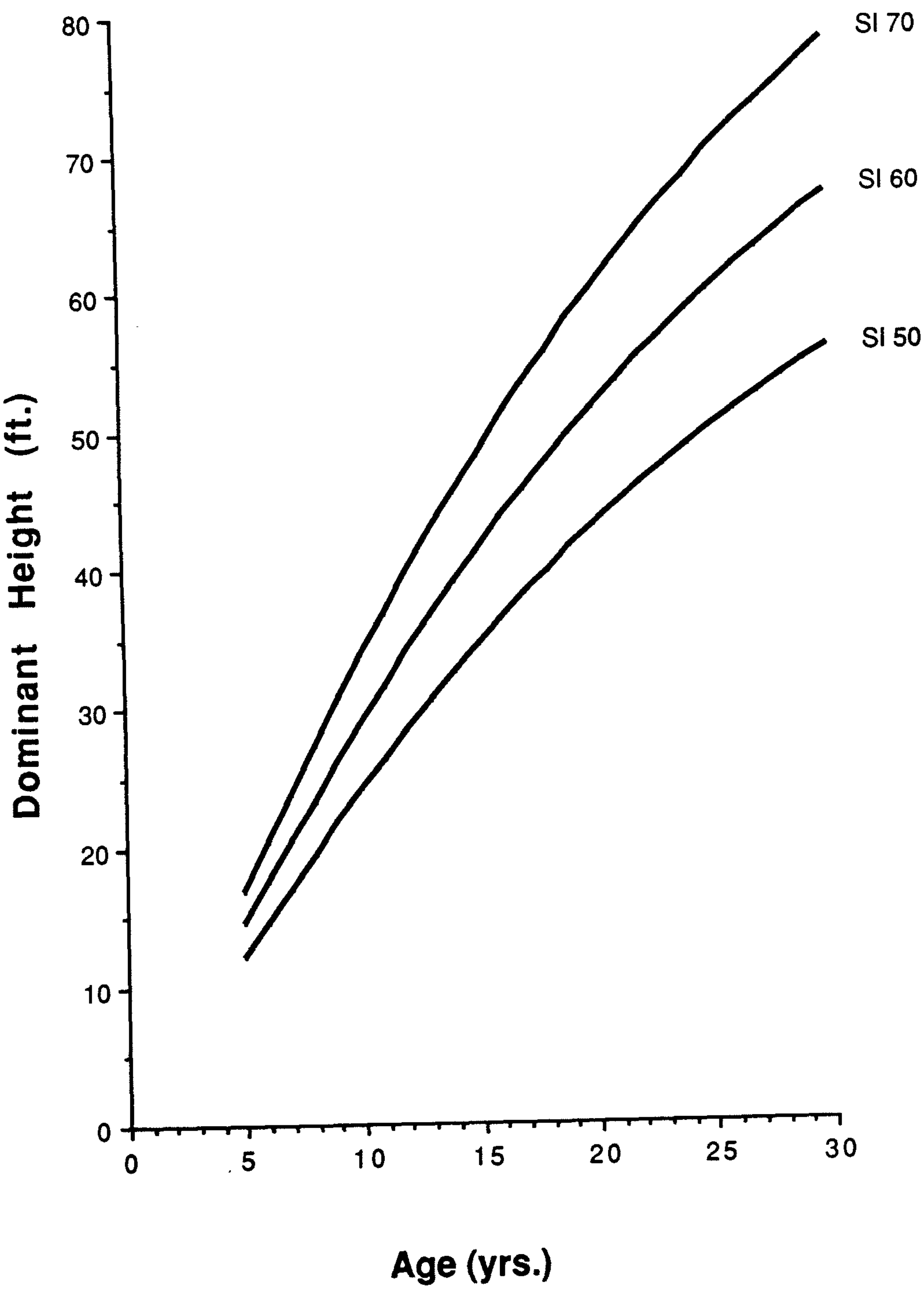
where S is the site index. Equation (3) was used to generate the three site index curves shown in Figure 2.

Basal Area Prediction and Projection

Over the range of stocking levels and ages represented in this data set, unthinned BS plots of the same age and with the same number of surviving trees per acre, produced more basal area per acre, the higher the average dominant/codominant height. And at a given location and age, more surviving trees produced more basal area.

Thinned plots with a given number of trees per acre, in general, have less basal area per acre than unthinned plots of the same age and the same number of trees per acre. For example, when a plot with 600 trees per acre at age 15, say, is thinned to 300 per acre, the average dbh of the 300 remaining trees is less than the average dbh of an unthinned plot with 300 trees per

Figure 2. Three site index curves generated by the site index equation (3).



acre at age 15, even when thinning selectively from below. The greater the thinning intensity, the greater the difference in basal area tends to be. For example, a plot thinned from 800 per acre to 300 has even less basal area than a plot thinned from 600 to 300 at age 15. Over time, the basal area of the thinned plot is expected to approach that of an unthinned plot with the same number of trees per acre.

A basal area prediction and compatible projection equation that accommodates these trends was fitted to the data.

$$\ln B = -4.2232 - 19.4910(1/A) + 1.3548(\ln H) + 0.5315(\ln N) + 4.5102(\ln H/A) + 1.1122(\ln N/A) - 0.2702(N_t/N_b)(A_t/A) \quad (4)$$

$n = 714 \qquad R^2 = 0.93 \qquad S_{y.x} = 13\%$ of predicted B

where B = basal area per acre in sq.ft.

A = plantation age in years

H = average dominant/codominant height in ft.

N = number of surviving trees per acre

N_t = trees per acre removed in thinning

N_b = trees per acre surviving immediately before thinning

A_t = age when thinning occurred

ln = natural logarithm

Plot measurements at the time of thinning in 1978 and 1980, and at the 1988 remeasurement for all BS and SAR plots were used to estimate the parameters simultaneously in the prediction equation (4) and the projection equation (5).

$$\ln B_2 = \ln B_1 - 19.491(1/A_2 - 1/A_1) + 1.3548(\ln H_2 - \ln H_1) + 0.5315(\ln N_2 - \ln N_1) + 4.5102(\ln H_2/A_2 - \ln H_1/A_1) + 1.1122(\ln N_2/A_2 - \ln N_1/A_1) - 0.2702(N_tA_t/N_bA_2 - N_tA_t/N_bA_1) \quad (5)$$

where B_1 and B_2, H_1 and H_2, N_1 and N_2 are the basal area per acre, the average dominant/codominant height, and numbers of surviving trees per acre at ages A_1 and A_2, respectively.

A simultaneous estimation procedure was used to estimate the parameters in the two equations (4) and (5), using the predicted basal area, and the projected survival and average dominant/codominant height in the projection equation (5).

Basal area yield curves generated with these equations for planting survival densities of 300, 450, 700 and 900 trees per acre at age 3 are illustrated in Figure 3 for a site index of 60 ft. For example, for the age 3 planting survival of 450 per acre, the expected survival at age 15 is 380 (equation 1), the average dominant/codominant height is 41.3 ft. (equation 3) and the predicted basal area is 69.1 sq.ft. (equation 4). At age 25 the survival is predicted to be 333 trees per acre, the average dominant/codominant height is 60 ft. and the basal area 102.3 sq.ft. per acre. The same result is obtained at age 25 with the projection equation (5) from age 3 to age 25, or from age 3 to age 15, and then from age 15 to age 25.

Basal area prediction and projection equations (4) and (5) can also be used to predict basal area growth in thinned plantations, as illustrated in Table 3 and Figure 3. Basal area predictions were calculated for site index 60 for unthinned plantations with age 3 planting survival densities of 700 and 300 trees per acre, and also for a plantation with age 3 planting survival of 700, and thinned from 590 to 253 at age 15. If left unthinned, the plantation with a planting survival of 700 trees per acre at age 3 is expected to have

Figure 3. Basal area growth curves generated with equation (4) for four different planting survival densities and for a thinned plantation.

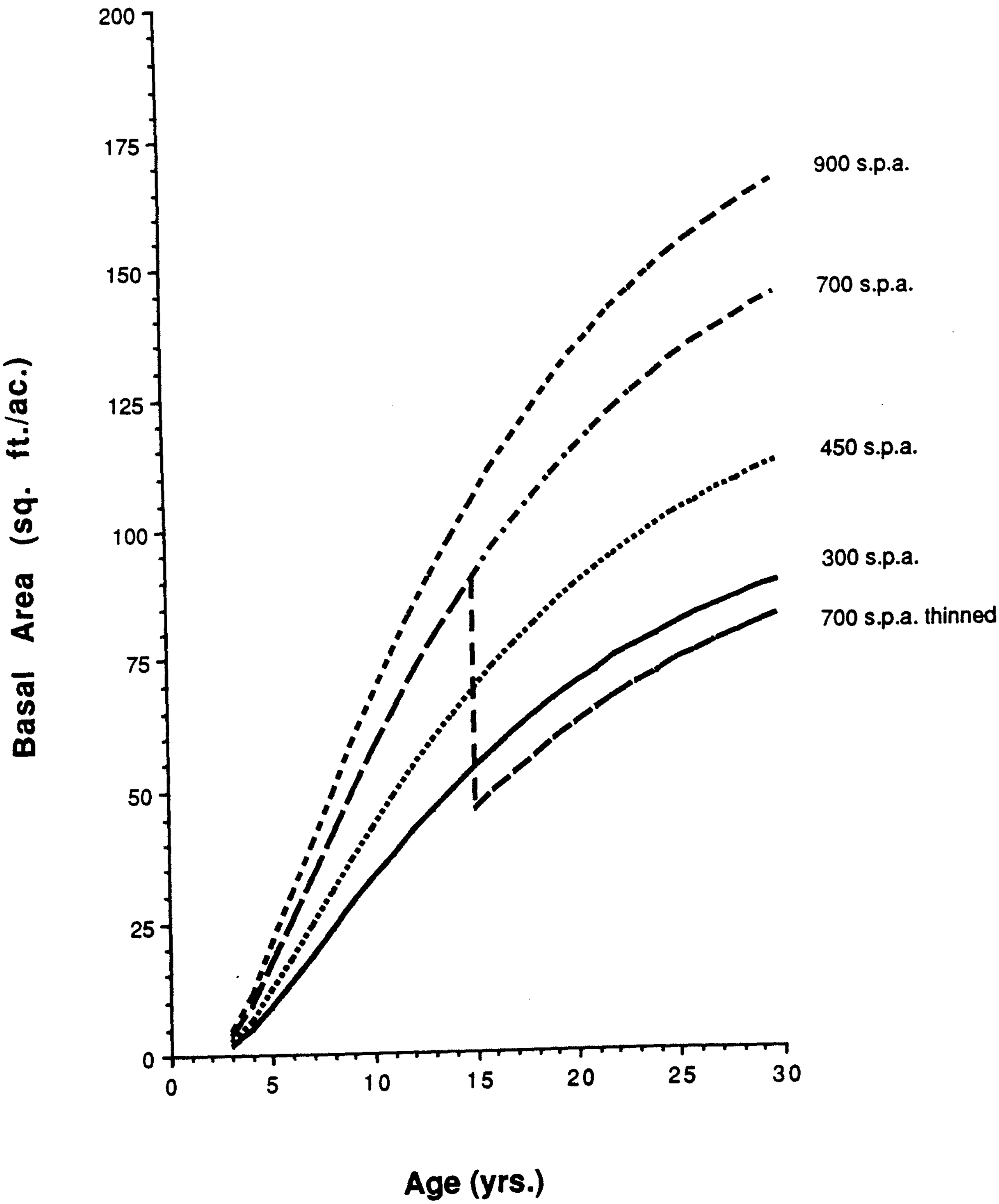


Table 3. Predicted basal area and total stem volume (i.b.) per acre for unthinned and thinned plantations on site index 60 land.

Age	Trees per acre Unthinned		Trees per acre Thinned	Basal area per acre Unthinned		Basal area per acre Thinned	Tot. vol per acre Unthinned		Tot. vol per acre Thinned
3	700	300	700						
10	632	271	632	56.9	33.0	56.9	631	362	631
15	590	253	590-253	90.1	54.0	90.1-46.3	1446	876	1446-683
20	552	237	237	114.2	69.5	61.9	2254	1400	1160
25	517	222	222	131.8	81.0	73.8	2982	1881	1618
30	485	208	208	144.0	89.0	82.4	3585	2283	2016

485 surviving trees with 144.0 sq.ft. of basal area per acre at age 30. An unthinned plantation with a planting survival of 300 trees per acre is expected to have 208 surviving trees and 89.0 sq.ft. of basal area per acre at age 30, while a plantation with a planting survival of 700 and thinned from 590 to 253 per acre at age 15 would yield 43.8 sq.ft. in the thinning, and 82.4 sq.ft. at age 30, for a total basal area production of 126.2 sq.ft. per acre.

Volume Prediction and Projection

Plot measurements at the time of thinning in 1978 and 1980, and at the 1988 remeasurement for all BS and SAR plots were used to estimate the parameters in a total stem volume inside bark prediction and projection equation. A simultaneous estimation procedure was used with age, predicted basal area, and projected survival and average dominant/codominant height as predictor variables in equations (6) and (7).

$$\ln TVIB = 2.6275 - 0.6725(\ln H/A) - 0.3875(\ln N) + 1.6193(\ln B) \quad (6)$$

$$n = 714 \qquad R^2 = 0.94 \qquad S_{y.x} = 195$$

where

TVIB = total inside bark stem volume in cu.ft. per acre

H = average dominant/codominant height in ft.

A = plantation age in years

N = surviving trees per acre

B = basal area per acre in sq.ft.

ln = natural logarithm

$$\ln TVIB_2 = \ln TVIB_1 - 0.6725(\ln H_2/A_2 - \ln H_1/A_1)$$
$$- 0.3875(\ln N_2 - \ln N_1) + 1.6193(\ln B_2 - \ln B_1) \quad (7)$$

where $TVIB_1$ and $TVIB_2$, H_1 and H_2, N_1 and N_2, B_1 and B_2 are the total volume, average dominant/codominant height, surviving trees per acre, and basal area per acre at ages A_1 and A_2, respectively.

Total volume yield curves in Figure 4 for age 3 planting survival densities of 300, 450, 700 and 900 per acre, were generated with these equations for site index 60 land. Also shown in Figure 4 and in Table 3 is the expected total stem volume yield for a plantation with a planting survival density of 700, thinned from 590 to 253 at age 15. Expected yield for the unthinned plantation with a planting survival of 700 is 3585 cu.ft. at age 30; for the unthinned plantation with 300 at age 3, the expected yield is 2283 cu.ft. The thinned plantation is predicted to yield 763 cu.ft. at age 15 and 2016 cu.ft. at age 30 for a total production of 2779 cu.ft. per acre.

The basal area and total stem volume prediction and projection equations can be used in a similar manner to predict yields for the range of planting survival densities and thinning intensities represented by this data set. Thoughtful choice of the model forms should allow modest extrapolation beyond the range of the data. In this particular study, as in many others, it seems clear, however, that management regimes that include thinnings will not produce as much total stem volume over reasonable rotations as will regimes without thinnings. Justification for management regimes that include thinnings must therefore stem from different product flows and cash flows. For this purpose a merchantable volume prediction equation proposed by Amateis and others (1986) was fitted to PMRC growth and yield plot data for site-prepared slash pine plantations in the lower coastal plain.

$$VIB_{t,d} = TVIB \exp[-0.5217(t/\bar{D})^{3.8386} - 0.6887N^{-0.1167} (d/\bar{D})^{5.7185}] \quad (8)$$

$$n = 1973 \qquad R^2 = 0.95 \qquad S_{y.x} = 18$$

where

TVIB = total inside bark stem volume in cu.ft. per acre

t = merchantable diameter limit outside bark in inches

d = minimum dbh limit in inches

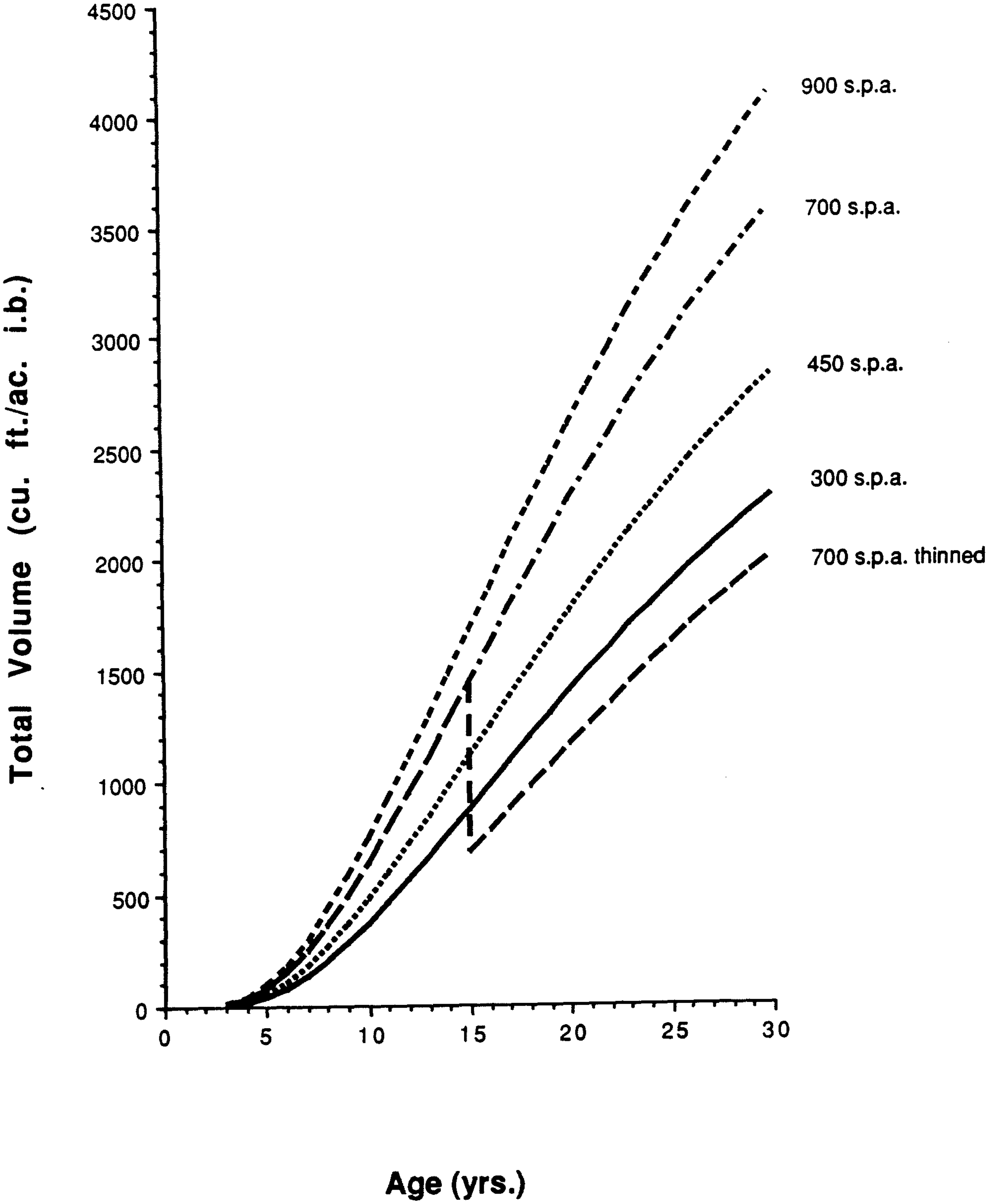
$\bar{D}$ = quadratic mean dbh in inches

N = surviving trees per acre

$VIB_{t,d}$ = inside bark stem volume to a t-inch diameter limit of trees with a dbh $\geq$ d inches in cu.ft. per acre

Equation (8) can be used to apportion the total per acre volume into various product size categories. For example, a plantation with site index 60 and an age 3 survival of 300 per acre, is expected to have 208 surviving trees with a basal area of 89.0 sq.ft. and total inside bark volume of 2283 cu.ft.

Figure 4. Total volume growth curves generated with equation (6) for four different planting survival densities and for a thinned plantation.



per acre at age 30, as shown in Table 3. Equation (8) is used to predict the volume in specified size categories, for example,

$$VIB_{3,4} = 2256 \text{ cu.ft. per acre}$$

is an estimate of total inside bark volume of trees with a minimum dbh of 4 inches and a minimum top diameter of 3 inches outside bark. This would be an estimate, say, of total merchantable pulpwood volume if this were the only product of interest. Similarly,

$$VIB_{6,8} = 1652 \text{ cu.ft. per acre}$$

is an estimate of total sawtimber volume of trees with a minimum dbh of 8 inches and top diameter of 6 inches. Large sawtimber or veneer log volume can be estimated as

$$VIB_{8,10} = 766 \text{ cu.ft. per acre}$$

Thus, the predicted pulpwood volume is 2256 - 1652 = 604 cu.ft. per acre, the chip-n-saw volume is 1652 - 766 = 886 cu.ft., and the large sawtimber volume 766 cu.ft.

Yield predictions by primary product classes such as these are particularly useful for more realistic evaluations of different management regimes. For example, to compare a regime that assumes a planting survival of 700 per acre and a clearcut at age 30 with one that has the same planting survival, a thinning to 253 trees per acre at age 15 and clearcut at age 30. The management regime without the thinning is expected to produce a total inside bark volume of 3585 cu.ft. at age 30 (Table 3), consisting of 1827 cu.ft. of pulpwood, 1402 cu.ft. of small sawtimber, and 262 cu.ft. of large sawtimber. On the other hand, the thinning regime would yield a total inside bark volume of 763 cu.ft. at age 15 of which 630 cu.ft. would qualify as pulpwood, and no sawtimber. Of the total of 2016 cu.ft. expected at age 30, 626 cu.ft. would be pulpwood, 828 cu.ft. small sawtimber, and 533 cu.ft. large sawtimber. Expected product yields for these two management regimes and for a planting survival of 300 per acre without thinning, are summarized in Table 4.

Table 4. Expected product yields in cu.ft. per acre for 3 management regimes for site index 60.

	Age	15	20	25	30
	pulpwood	1276	1798	1911	1827
Unthinned(700)	chip-n-saw	--	323	899	1402
	large sawtimber	--	--	62	262
	total merchantable	1276	2121	2872	3491
	pulpwood	673(630)	745	706	626
Thinned(700)	chip-n-saw	--	349	676	828
590 to 253	large sawtimber	--	24	202	533
at age 15	total merchantable	673(630)	1118	1584	1987
	pulpwood	697	757	687	604
Unthinned(300)	chip-n-saw	129	525	680	886
	large sawtimber	--	79	482	766
	total merchantable	826	1351	1849	2256

Weight Prediction and Projection

Pulp yield is more highly correlated with dry wood weight than with green volume yield. For this reason per-acre dry wood weight prediction and projection equations, of the same form as the volume equations, were estimated, namely

$$\ln DWIB = -1.1192 - 1.8680(\ln H/A) - 0.5402(\ln N) + 1.7524(\ln B) \qquad (9)$$

$n = 714 \qquad R^2 = 0.91 \qquad S_{y.x} = 3.9$

where

DWIB = dry wood weight in tons per acre

H = average dominant/codominant height in ft.

A = plantation age in years

N = surviving trees per acre

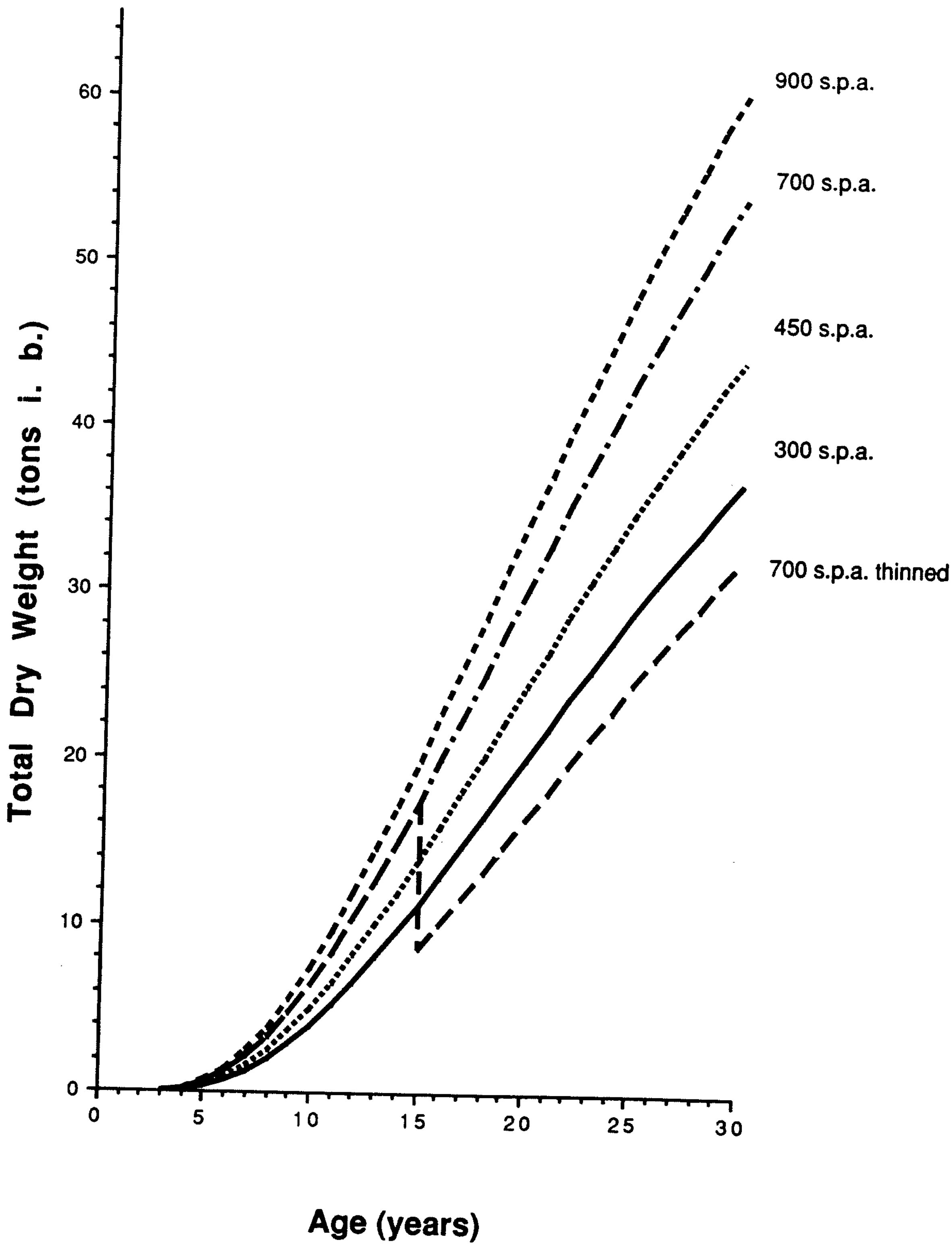
B = basal area per acre in sq.ft.

And the projection equation

$$\ln DWIB_2 = \ln DWIB_1 - 1.8680(\ln H_2/A_2 - \ln H_1/A_1) - 0.5402(\ln N_2 - \ln N_1) + 1.7524(\ln B_2 - \ln B_1) \qquad (10)$$

The yield curves for planting survival densities of 300, 450, 700 and 900 per acre shown in Figure 5 were generated with these equations. Also shown is the expected weight yield for a plantation thinned from 590 to 253 at age 15.

Figure 5. Total dry weight growth curves generated with equation (9) for four different planting survival densities and for a thinned plantation.



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