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Growth of a slash pine spacing study five years after thinning

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GROWTH OF A SLASH PINE SPACING STUDY FIVE YEARS AFTER THINNING

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

In 1994, a 17 yr old, slash pine spacing study was thinned to 35% of the maximum stand density to evaluate the influence of prethinning stand conditions on postthinning growth after thinning to a common stand density. It was expected that plots thinned to a common growing stock level should have equal growth increments and if growth was not equal then the difference was related to prethinning stand conditions. Stand growth variables of quadratic mean diameter increment, stand-level basal area increment, and gross-volume increment were evaluated to determine the influence of initial spacing, stand density, and prethinning crown size before thinning and for 5 years after thinning.

Lower values of relative stand densities were associated with initially wider spacings before thinning and higher values 2-5 yr after thinning. Before thinning, quadratic mean diameter increment was positively related to initial spacing and prethinning crown dimensions and negatively related to relative stand density. After thinning, quadratic mean diameter increment was not significantly influenced by initial spacing, but it was inversely correlated with prethinning crown ratio 5 yr after thinning as relative stand density increased. Stand-basal area increment was negatively correlated with prethinning crown width, crown ratio, and crown volume before thinning, but it was not significantly related to initial spacing or relative stand density before or after thinning. Gross-volume increment was positively influenced by initial spacing and prethinning crown dimensions and negatively related to relative stand density prior to thinning. These positive relationships were observed during yr 2, 3, and 4 after thinning where wider initial spacings produced larger increments in volume as relative stand densities increased.

Prethinning crown dimensions remained correlated with gross-volume increment after thinning. However, after thinning, these correlations with prethinning crown dimensions held a consistent relation with postthinning growth and also conformed to conventional growth-growing stock relationships as stands developed. The significant relationships detected between gross-volume increment and initial spacing, prethinning crown dimensions, and relative stand densities support that prethinning tree characteristics affected postthinning gross-volume increment for the duration of this study.

INTRODUCTION

Several million hectares in the coastal plains have been devoted to developing slash pine (*Pinus elliottii* var. *elliottii*) plantations. Because of its rapid growth and high quality fiber, slash pine can produce high volumes of wood for paper, plywood, and lumber at an early age allowing early monetary returns. It has a very low resistance to ice damage, drought, and cold tolerance, but a high resistance to poor drainage. Growth stagnation often occurs in overstocked stands of slash pine (Bennett and Jones 1981). Slash pine can be found beyond its natural range and is especially aggressive on cutover areas and moist soils.

In plantations, stand density is controlled through initial spacing of seedlings and with thinning, both of which influence the growing space of the trees. Although there is often uncertainty when determining the growth response of thinned stands, how trees are initially spaced largely determines the growth after thinning (O'Hara 1989, Wiley and Zeide 1992, Adams and Clason 2002). Thinning is an important silvicultural practice for improving tree growth by redistributing growth and increasing the growth rate of residual trees. This often results in increased diameter growth of residual trees and allocates growth to better trees in the stand. Manipulating stand density can influence species establishment, modify stem quality, rate of diameter growth, and volume production during stand development (Daniel et al. 1979). By controlling growing stock through initial spacing and thinning, foresters can select trees to which additional growth will be allocated and maintain stand density in a range that fully utilizes the site.

Typically, when choosing an appropriate planting spacing and thinning treatment, silviculturists must decide between individual tree growth and total stand growth. Because stand growth cannot be maximized at the same time as individual tree growth, a silvicultural trade-off between both aspects of growth is an obvious consequence for management objectives. Studying the relationship between growth and growing stock help determine this silvicultural trade-off. Stand yields are usually highest at higher densities because tree occupancy is approaching its upper limit (Long 1985). When stands are below its upper growing stock limit, stand growth is considerably below its potential and individual tree growth is maximized (Long 1985). Stands that are densely stocked can stagnate; however, they can still produce large quantities of fiber (Long and Smith 1990), but only produce marginal yields (Mann and Lowery 1974).

Numerous spacing and thinning trials have been designed to better understand the impact of density and spacing on tree growth and stand development. In general, greater growth responses occur when thinning is done at relatively young ages because individual tree crowns are large, vigorous, and able to respond with increased growth (Harrington 2001a). Holley and Stiff (2004) determined that diameter increment was lowest for the highest density and increased with decreasing residual density. Wilson (1955), Gruschow and Evans (1959), and Andrulot et al. (1972) found similar volume growths over a range of stocking densities indicating fewer trees produce similar annual volume growth, whereas Hibbs et al. (1989) found that thinning decreased stand volume growth. Wide spacings result in less volume and basal area per unit area than close spacings, but lower planting densities have larger average diameters than higher densities (Lee and Lenhart 1998). Cochran and Barrett (1998) found that lower densities produce larger trees with higher volumes per tree, and at times, higher stand board-foot volumes. Differences in initial density have been found to also influence the development of stand density in conjunction with thinning (Pienaar and Shiver 1984, O'Hara and Oliver 1988, McFadden and Oliver 1988). Earlier findings by Assmann (1970), Hamilton (1976), and Pienaar (1979) confirmed that thinning did not increase total stand production density, however, Clutter et al. (1983), found that it can shift the distribution of growth to larger trees.

Understanding how crown variables determine the silvicultural trade-off for growth-growing stock relationships is another important aspect of stand development. During stand development, interactions between the size and shape of individual trees and crowns and the structure and density of forest stands are important in determining the growth behavior of both trees and stands. The impact of competition among trees can easily be seen at the canopy level through the influence of competitors on the dimensions and structure of individual tree crowns (Perry 1985, Maquire and Hann 1990). Using crown characteristics to examine growth relationships between crown and stem is advantageous because crown, stem, and stand attributes are interrelated and can help predict future values of certain stem and stand characteristics (Sprinz and Burkhart 1987). Sprinz and Burkhart (1987) found that stem growth was related to crown growth, while stand dimensions were also related to crown dimensions in unthinned loblolly pine (*Pinus taeda*) plantations.

Stand density affects stem growth mostly through its effect on crown size because canopy properties are significantly related to growth (Larson 1963). Crown expansion begins after thinning and proceeds until competition restricts it from further development. Since crown dimensions reflect measures of growing space, direct measures of crown size serve as indications of a tree's ability to fully occupy its available growing space. Many expressions of crown size are strongly correlated with volume, height, or diameter growth of trees within a given stand. Expressions of gross crown size examined during growth analyses have varied widely but include crown length (Hamilton 1969, Van Laar 1969), crown diameter (Van Laar 1969), crown ratio (Burkhart et al. 1987), crown volume (Hamilton 1969, Van Laar 1969), and many other crown measures (e.g., crown surface area, crown projection area, and leaf area). The same factors or conditions that determine the size and distribution of the crown also influence stem form. Significant relationships between stem size and crown dimensions have been reported in the literature, but have not covered a wide range of ages and stand densities. Bonnor (1964), Curtis and Reukema (1970), and Dyer and Burkhart (1987) tested the effects of different stand densities, initial spacings, or thinnings on the relationship between crown and stem dimensions. Some studies confirmed that stand density had an effect on the relationship (e.g., Curtin 1964, Smith and Bailey 1964); while other studies inferred that stand density did not have a significant effect (e.g., Bonnor 1964, Minckler and Gingrich 1970).

Intrinsic effects of prethinning crown size are expected where larger trees should reflect larger crown sizes and smaller trees, smaller crown sizes. Because crown structure is influenced by initial spacing, crown structure after thinning should reflect those traits characterized by initial spacing and any differences in growth should be due to the conditions prior to thinning. It is assumed that after thinning to the same stand density, there will be no residual impact on growth rates regardless of initial spacing. If any patterns are seen, then the relationships should relate back to initial spacing as well as prethinning crown size.

Stand density at the time of thinning is expected to have an effect on growth before thinning. Prethinning quadratic mean diameter increment is anticipated to be highest on lower density stands and lowest for higher density stands. Prethinning stand density is likely to influence postthinning basal area and volume increments. Generally, no differences in postharvest growth are expected because stands of the same age and on the same site, with equal stand densities are expected to grow the same regardless of tree numbers and size. However, an inverse relationship between quadratic mean diameter increment and residual density is probable as well greater stand-level basal area increment and gross-volume increment with increased residual density according to Feduccia (1979).

Since both stand and tree growth are functions of growing stock, stands of the same age and density growing on the same sites should have equal growth rates. However, when thinning is involved, potential tree growth is possibly more strongly related to stand density prior to thinning for some time after thinning because growth of residual trees is usually rapid immediately after thinning while stands readjust to the newly added growing conditions. With the expectation that plots thinned to a common growing stock level should exhibit the same growth rate, any differences in growth should be due to stand conditions prior to thinning.

Research Objectives and Hypotheses

The primary purpose of this research is to analyze the magnitude and duration of the effects of prethinning stand conditions on postthinning growth. Specific objectives of this study were to (1) determine how initial spacing influenced stand density before thinning and for five years after thinning to a common stand density, and (2) evaluate the influence of initial spacing, stand density, and prethinning crown size on quadratic mean diameter increment, stand-level basal area increment, and gross-volume increment before thinning and for five years after thinning. To evaluate how prethinning crown size and postthinning stand growth are related after stands were thinned to a common stand density, the effects of initial spacing on the growth variables must first be determined. The major hypothesis is that equal stand densities should have equal growth increments and if growth was not equal then the difference was related to prethinning stand conditions. Postthinning growth-growing stock relations were also analyzed to see if the relationships agreed with prethinning growth-growing stock relations.

MATERIALS AND METHODS

Site Description

The study area is located about 1.6 km east of Woodworth, LA, in Rapides Parish, on the Alexander State Forest. The site was established on a cutover longleaf pine stand during the winter of 1976. The soil consists of a Kolin silt loam (fine-silty, siliceous, thermic Glossaquic Paleudalf) with a clayey subsoil from 0.3 to 0.6 m below the ground surface that restricts internal drainage. A slight slope in topography of 1 to 5% allows adequate runoff of surface water. Site index at base age 25 years is approximately 21 m based on the average height of the dominant and codominant trees in the stand measured at age 17 yr.

Climatic Conditions

The 1990's was the warmest and most rapidly warming decade in the 20th Century, both globally and in the U.S. (Boesch 2002) due to the rising temperatures in the latter decades. The National Climate Data Center in Asheville, North Carolina, confirmed that from April to June 1998, an extraordinary sequence of record breaking temperatures lead to the warmest period in 104 yr on record in Florida, Texas, Louisiana, and Arkansas exceeding the previous record in June of 1994. Based on 1990-2000 climate data from the Louisiana Office of State Climatology, average annual daily maximum and minimum temperatures in Rapides Parish were 25°C and 13°C, respectively, and the mean annual precipitation was 1450 mm. When thinning treatments were applied in 1994, mean annual precipitation averaged 1880 mm for two consecutive years providing ample rainfall across the area. Climate data for south LA also chronicled a 24-month drought caused by the La Niña event in the spring of 1998. The arrival of La Niña led to increased temperatures from 1998 through 2000 where temperatures rose above 32°C for an average of 104 days during the summer. For the period 1996-2000, mean annual precipitation fell to a range of 1018-1357mm. This period of dryness and elevated temperatures ranks as the driest period observed within the past century (Grymes 2001). For the duration of this study, the extended drought continued to be a major stress factor across much of the region.

Study Design

The original study was designed to examine the growth and yield of genetically improved slash pine seedlings planted at various spacings. Seven spacing treatments (1.2 x 1.2, 1.2 x 1.8, 1.8 x 1.8, 1.8 x 2.4, 2.4 x 2.4, 3.0 x 3.0, and 4.3 x 4.3 m) were randomly assigned to plots within five blocks. A total of 35 plots were created for the study. Each measurement plot consisted of 8 rows of 8 trees regardless of spacing, creating plots of varying sizes. A 10-m isolation strip comprised of trees with the same spacing surrounded each measurement plot.

Thinning Treatments

Baldwin et al. (1995) initiated the thinning study in 1994 when stands were 17 yr of age to compare the growth after thinning to a common value of Reineke's stand density index (SDI) and to the growth after thinning to a common value of basal area/ha (BA). Reineke's stand density index (SDI) expresses stand density as a function of quadratic mean diameter (Dq) and trees/ha (TPH). It is expressed in terms of the equivalent number of trees/ha in a stand at a standard diameter of 25 cm with the equation

[1] $SDI = TPH\ (Dq/25)^{1.6}$

(Reineke 1933).

Basal area/ha is also function of Dq and TPH and is calculated with the equation

[2] $BA = 0.00007854(TPH)(Dq)^2$.

Stand density was expressed as a percent of maximum SDI and BA for slash pine. The most recent estimate of the maximum SDI is 1110 (Dean and Jokela 1992). Dean and Baldwin (1993) reported that the maximum basal area for slash pine is 50.5 m^2/ha for this geographical area. Plots that were greater than 45% of the maximum SDI or BA were thinned to a residual density of 30% maximum SDI or maximum BA. Lower and upper threshold values of 30% and 45% respectively, for both SDI and BA based treatments were set to maintain full site occupancy while avoiding self-thinning (Long 1985). Self-thinning occurs at approximately 60% of the maximum density, and canopy closure occurs at approximately 25% of the maximum density for slash pine. The 4.3 x 4.3 m spacings were not included in this study because the average stand density was ≤ 30 % of the maximum SDI or maximum BA when the thinning treatments were applied (Table 1).

Before this study was established, fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) accounted for most of the mortality (Ferguson and Baldwin 1995). Shortly after thinning, an ice storm occurred in February 1996. Ice accumulations, specifically deposits within the crowns, and branch loss had damaged a considerable number of trees after thinning. The smaller trees in the closer spacings were more prone to bending, whereas larger crowned trees in wider spacings were more inclined to breaking. Two of the spacing treatments (1.2 x 1.2 and 1.2 x 1.8 m) were eliminated from this study because of the ice damage.

After thinning, measurements indicated that plots were thinned closer to values of 35% of the maximum stand density rather than the original 30% target values (Table 1). At the time of thinning, the optimal timing for first thinning of the narrower spaced plots (1.8 x 1.8, 1.8 x 2.4, and 2.4 x 2.4-m spacings) was probably years earlier because the average densities for these plots ranged from 63% to 68% of the maximum SDI and from 56 to 62% of the maximum BA, well beyond the upper limit of growing stock set for this study. Thinning was timely for the widest spaced plots (3.0 x 3.0-m spacings) with an average density of 45% of the maximum BA and SDI at age 17 yr.

Table 1. Before and after thinning values using two thinning methods in 17 yr old stands of slash pine at various spacings in Woodworth, LA, USA. (Data from Baldwin et. al 1995).

Thinning Method	Initial Spacing (m)	Before Thinning	After Thinning
		----------------------% Maximum SDI[a]----------------------	
SDI	1.8 x 1.8	68	35
	1.8 x 2.4	68	34
	2.4 x 2.4	63	35
	3.0 x 3.0	45	34
	4.3 x 4.3	28[b]	N/A
	Target		30
	Actual		35
		----------------------% Maximum BA[a]----------------------	
BA	1.8 x 1.8	60	34
	1.8 x 2.4	56	33
	2.4 x 2.4	62	35
	3.0 x 3.0	45	35
	4.3 x 4.3	30[b]	N/A
	Target	30	30
	Actual	34	34

[a] Percent expressed based on maximum SDI (1110) or maximum BA (50.5 m^2/ha) for slash pine.
[b] Plots did not meet the thinning criteria.

Measurements

Trees on all plots were measured annually for the first 10 yr of growth, again at age 15 yr, before and after thinning at age 17 yr and for each of five years after thinning until age 22. Field measurements were taken in the winter of each year in either January or February and consisted of diameter at breast height (1.37 m), height to the base of the live crown, total height, crown width in two directions at right angles, and crown class.

Increment in quadratic mean diameter was calculated from plot values for each spacing treatment for each measurement period. Quadratic mean diameter increment (I_D) was the annual increment in quadratic mean diameter. Gross basal area increment (I_B) was the summation of annual individual tree increments in basal area, the cross-sectional area of a tree measured at 1.37 m, and was expressed as per hectare values. Gross volume increment (I_V) was the summation of annual individual tree increments in volume and was expressed as per hectare values.

Average initial crown variables were calculated using prethinning individual-tree data to calculate an average for each plot. Crown width (C_W) was averaged for each tree then averaged by plot. Other crown dimensions calculated based on plots means consisted of crown length (C_L) calculated by subtracting the height to the base of the live crown from the total height, live-crown ratio (C_R) calculated by dividing the live crown by total height, and crown volume (C_V) calculated as the volume of a right angle cone using average C_W per tree and C_L as width and length measurements, respectively.

Statistical Analyses

Simple ANOVA (analysis of variance) was used to test the hypothesis that diameter, basal area, and volume increment were the same across the thinned plots by testing for initial spacing effects on these various increments. If significant effects were detected, further analyses were conducted to investigate the correlation between the various increments and initial spatial and prethinning crown dimensions. Postthinning growth-growing stock relations were investigated by regressing the various increment values of each growth interval on the stand density at the start of the growth interval. For all analyses, a significance level of $\alpha = 0.10$ was selected.

<u>Initial Spacing Effects on Growth Increments</u>

Quadratic mean diameter increment, gross basal area increment, and gross volume increment were analyzed with a randomized block design with a mixed-model ANOVA (Littell et al. 1996) to test the effect of initial spacing on increment variables before thinning and each of the five subsequent years. To test whether postthinning increment was equal across initial spacing, sources of block and initial spacing effects were tested for significant effects on I_D, I_B, or I_V by using the following statistical linear model:

[3] $$Y_{ij} = \mu + B_i + S_j + \varepsilon_{ij},$$

where Y_{ij} denotes I_D, I_B, or I_V for the i^{th} block and j^{th} initial spacing, μ is the population mean, B_i is the effect of block i (i = 1…5), S_j is the effect of initial spacing j, and ε_{ij} is the random error associated with each observation for block i and initial spacing j. Block effects were considered random, and the experimental error and initial spacing were fixed effects. This approach was used to test if initial spacing influenced any of the growth variables.

Additional examination of the influence of initial spacing on I_D, I_B, and I_V was performed by comparing individual treatment means. When ANOVA indicated significant differences among treatments, individual comparisons were then tested using the Tukey adjustment. Also, orthogonal, polynomial contrasts were investigated to test for significant linear, quadratic, or cubic patterns in means between initial spacings with regard to I_D, I_B, or I_V. As suggested by J. Geaghan (personal communication, May 2005), the Interactive Matrix Language's Orthogonal Polynomial function (SAS Version 9.1, Cary, NC) was used to generate the appropriate coefficients for the orthogonal linear combination statement in the mixed model. This was recommended because the initial spacing treatments were unequally spaced.

Associations between Prethinning Crown Dimensions and Growth Increments

Correlation analyses were performed using prethinning crown dimensions of C_W, C_L, C_R, and C_{VOL} with I_D I_B, and I_V before thinning and for the five measurement periods after thinning. The following hypotheses were used to test the association between prethinning crown dimensions and I_D, I_B, and I_V:

H_0: $\rho=0$, and

H_A: $\rho\neq0$

The null hypothesis stated that the correlation between prethinning crown dimensions and I_D, I_B, and I_V was zero and there was no relationship. The alternate hypothesis stated that the correlation between prethinning crown dimensions and I_D, I_B, and I_V was significantly different from zero and was either a positive or negative relationship.

RESULTS AND DISCUSSION

Crown Dimensions

During competition, changes in the canopy determine the relationship between tree sizes and stand density, and therefore, determine the rate of stem growth. All prethinning crown dimensions of crown width (C_W), crown length (C_L), crown ratio (C_R), and crown volume (C_{VOL}) at age 17 yr showed significant differences between initial spacings ($P<0.001$) (Table 2). Prethinning crown dimensions increased with initial spacing where the greatest dimensions were found in the widest spacing. Dean and Baldwin (1996) indicated how important it was to maintain vigorous crowns and growth rates when managing density at early ages. Smaller values of C_R often result from earlier effects of density and are carried late into stand development which sets the potential growth rate of the stand (Harrington 2001b). Consequently, C_R was already below 50% for all initial spacings prior to thinning indicating increased competition. The decline in C_R from wider spacings to closer spacings indicated that live-crown ratios were diminishing and diameter growth was slowing as C_R was falling below 40% (Harrington 2001b). The smaller crown ratios suggest that postthinning growth could be influenced since the minimum live crown ratio necessary for a prompt thinning response is 40%.

Diameter and I_D

Quadratic mean diameter (Dq) was significantly influenced by initial spacing before thinning at age 17 yr and 5 yr after thinning ($P<0.001$) (Table 3). Multiple comparisons between the different initial spacings revealed that the Dq in each of the initial spacings was significantly different from the other before thinning at age 17 yr and increased with increasing initial spacing. At age 22 yr, the two widest initial spacings were significantly different from the two closest initial spacings and Dq continued to increase with increasing initial spacing. Overall, the larger the initial area associated with each tree, the greater the Dq.

Table 2. Average prethinning crown dimensions for each initial spacing at age 17 yr (before thinning) for slash pine near Woodworth, LA. Like letters show no significant differences using the Tukey method at the α = 0.10 level (degrees of freedom for error term = 12).

Initial Spacing	C_W	C_L	C_R	C_{VOL}
------m x m------	----------------m-----------------		%	m^3
1.8 x 1.8	2.77a	6.19a	37a	5.29a
1.8 x 2.4	3.25b	6.66ab	40b	6.70b
2.4 x 2.4	3.50c	7.10b	41b	7.69b
3.0 x 3.0	4.12d	7.95c	46c	10.13c
Pr > F	< 0.001	< 0.001	< 0.001	< 0.001
SE[a]	0.0635	0.1675	0.0092	0.2777

[a] Standard error

Table 3. Quadratic mean diameter (Dq) values for each initial spacing at age 17 yr (before thinning) and age 22 yr (5 yr after thinning) for slash pine near Woodworth, LA. Like letters show no significant differences using the Tukey method at the α = 0.10 level (degrees of freedom for error term = 12).

Initial Spacing	Age (yr)	
(m)	17	22
	----------------cm----------------	
1.8 x 1.8	15.7a	21.8a
1.8 x 2.4	17.0b	22.7a
2.4 x 2.4	18.2c	24.3b
3.0 x 3.0	20.9d	26.2c
Pr > F	<0.001	<0.001
SE[a]	0.2035	0.3614

[a] Standard error

Prethinning quadratic mean diameter increment (I_D) was strongly influenced by initial spacing for the 16-17 yr growth interval (P<0.001) (Figure 1). A linear pattern was also detected using orthogonal polynomial contrasts (P<0.001). Multiple comparisons between the different initial spacings revealed that the 3.0 x 3.0 m spacing had significantly higher I_D than the other spacings before thinning.

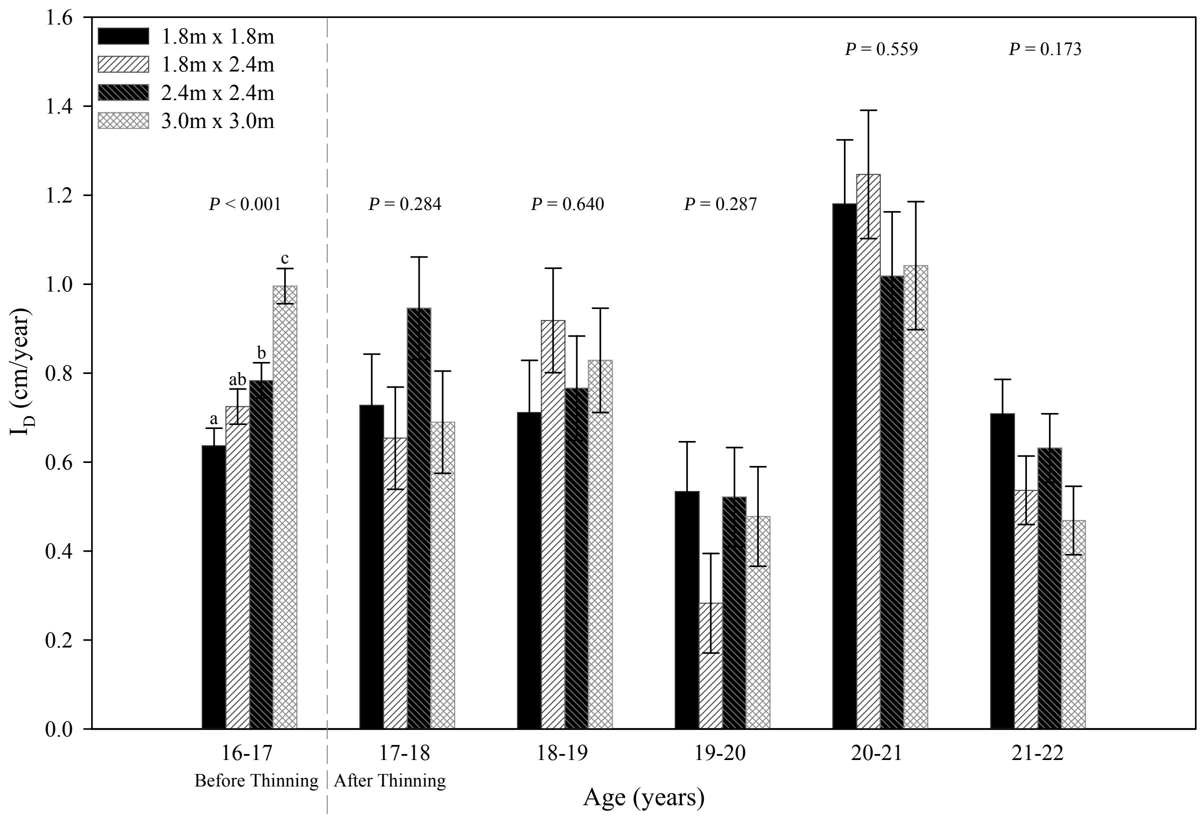

Figure 1. Quadratic mean diameter increment (I_D) for each spacing at the growth interval 16-17 yr before thinning and after thinning for growth intervals 17-22 yr for slash pine near Woodworth, LA (n = 20). Like letters show no significant differences using the Tukey method at the $\alpha = 0.10$ level and vertical bars represent the root mean squared error for each age (degrees of freedom for error = 12).

Harrington (2001a) explained that Dq responses to thinning are more obvious and more prolonged when first thinnings occur early in stand development (e.g., 10 to 15 yr after planting) and at high thinning intensities. Although thinning was delayed for many of these slash pine plots and plots were thinned to the same density level, initial spacing did not significantly influence I_D (all P≥0.173) after thinning (Figure 1).

Prior to thinning, a positive correlation appeared between prethinning crown variables and I_D (P≤0.001) (Table 4) for the 16-17 yr prethinning growth interval. Simple correlation coefficients between I_D and prethinning C_W, C_L, C_R, and C_{VOL} ranged from 0.76 to 0.80. Faster I_D corresponded with increased prethinning crown dimensions. Wider-spaced, larger-crowned trees exhibited greater I_D than closer-spaced, smaller-crowned trees. This strong correlation between I_D and crown dimensions prior to thinning agrees with previous results (e.g., Curtin 1964, Smith and Bailey 1964, Hamilton 1969).

Table 4. Correlation coefficients relating prethinning crown width (C_W), crown length (C_L), crown ratio (C_R), and crown volume (C_{VOL}) to quadratic mean diameter increment (I_D) for the growth interval 16-17 yr before thinning and after thinning for growth intervals 17-22 yr for slash pine near Woodworth, LA (n = 20).

Crown Variable	Growth Interval (yr)					
	16-17	17-18	18-19	19-20	20-21	21-22
C_W	0.78*	0.06	0.07	0.01	-0.25	-0.37
C_L	0.78*	-0.04	0.01	0.01	-0.29	-0.24
C_R	0.76*	0.04	0.03	-0.06	-0.29	-0.41*
C_{VOL}	0.80*	0.01	0.04	0.02	-0.27	-0.31

*Significant at α = 0.10

Correlations between I_D and prethinning crown dimensions did not exceed an absolute value of 0.37 after thinning, excluding C_R at the 21-22 growth interval; thus, no correlations existed between I_D and prethinning crown dimensions after thinning (Table 4). The appearance of the increasingly negative correlation coefficients in the latter growth intervals after thinning suggests an emerging inverse pattern between prethinning crown dimensions and I_D. The correlation between I_D and C_R was significant for the 21-22 yr growth interval (P=0.075). Based on these results, the initial hypothesis that plots thinned to a common stand density would have equal value of I_D could not be rejected with these data.

Basal Area and I_B

Basal area per hectare was influenced by initial spacing before thinning at age 17 yr and 5 yr after thinning (P=0.002) (Table 5). Prior to thinning, multiple comparisons between the different initial spacings revealed that the BA in the widest initial spacing (3.0 x 3.0 m) was significantly less than the BA of the other initial spacings. As seen in Holley and Stiff (2004), growth was being produced on so few trees before thinning for the wider-spaced stands that it did not contribute greatly to the overall BA whereas smaller spaced stands had more trees/ha and

Table 5. Stand basal area (BA) for each initial spacing at age 17 yr (before thinning) and age 22 yr (5 yr after thinning) for slash pine near Woodworth, LA. Like letters show no significant differences using the Tukey method at the $\alpha = 0.10$ level (degrees of freedom for the error term = 12).

Initial Spacing (m)	Age (yr) 17	22
	--------------m^2/ha--------------	
1.8 x 1.8	33.3a	18.3a
1.8 x 2.4	28.8b	18.6a
2.4 x 2.4	29.2ab	22.4b
3.0 x 3.0	24.0c	23.6b
Pr > F	0.002	0.002
SE[a]	1.3040	0.9293

[a] Standard error

contributed greatly to the overall BA. Five years after thinning, multiple comparisons between the different initial spacings revealed that the two wider initial spacings (2.4 x 2.4 and 3.0 x 3.0

m) were significantly greater in BA than the two closer initial spacings (1.8 x 1.8 and 1.8 x 2.4 m). This inverse relationship showed that BA increased faster in plots that were initially at lower stand densities and wider spacings than plots that were initially at higher stand densities and closer spacings.

Basal area increment (I_B) was not significantly influenced by initial spacing before thinning for the 16-17 yr growth interval (P=0.228) or after thinning (all P≥0.149) (Figure 2). After thinning to the same SDI, some plots contained more trees of a smaller size while others contained less trees of a larger size. Therefore, smaller increments offset by high tree numbers continued after thinning.

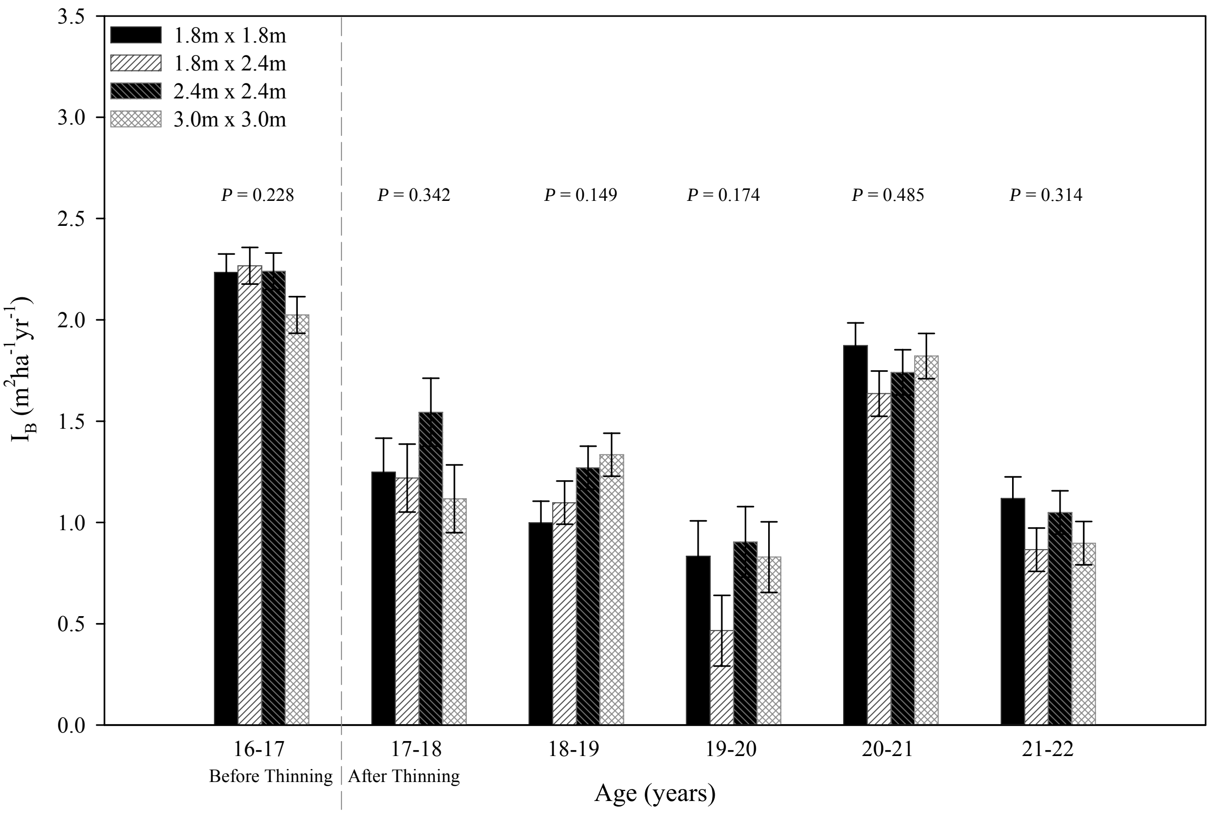

Figure 2. Stand-level basal area increment (I_B) for each spacing at the growth interval 16-17 yr before thinning and after thinning for growth intervals 17-22 yr for slash pine near Woodworth, LA. Vertical bars represent the root mean squared error for each age (degrees of freedom for error = 12).

Prethinning I_B was significantly correlated with prethinning crown dimensions ($P \leq 0.055$) (Table 6), with the exception of crown length ($P=0.120$). Simple correlation coefficients ranged from –0.36 to –0.48. This negative correlation between prethinning crown variables and I_B suggests that greater I_B was observed in closer-spaced plots with smaller-crowned trees before thinning which was expected since higher density stands usually have higher growth (Langsaeter 1941).

Table 6. Correlation coefficients relating prethinning crown width (C_W), crown length (C_L), crown ratio (C_R), and crown volume (C_{VOL}) to basal area increment (I_B) for the growth interval 16-17 yr before thinning and after thinning for growth intervals 17-22 yr for slash pine near Woodworth, LA (n = 20).

Crown Variable	Growth Interval (yr)					
	16-17	17-18	18-19	19-20	20-21	21-22
C_W	-0.46*	-0.03	0.45*	0.09	-0.07	-0.17
C_L	- 0.36	-0.12	0.40*	0.07	-0.19	-0.08
C_R	-0.48*	0.02	0.41*	0.02	-0.17	-0.18
C_{VOL}	-0.44*	-0.09	0.42*	0.08	-0.11	-0.11

*Significant at $\alpha = 0.10$

Significant correlations did not exist between I_B and prethinning crown dimensions at the 17-18 yr growth interval ($P \geq 0.604$) (Table 6). Simple correlation coefficients between I_B and prethinning crown dimensions were statistically significant ($P<0.080$) for the 18-19 yr growth interval suggesting some relation with crown size where larger I_B was associated with larger-crowned trees. This association was perhaps linked to the ice damage that occurred during that growth interval since smaller-crowned trees were primarily damaged. Prethinning crown dimensions exhibited no association with I_B thereafter as no significant correlations between I_B and prethinning crown dimensions were detected ($P>0.410$). The appearance of negative correlation coefficients 4 and 5 yr after thinning suggest that patterns that existed before thinning may have been reemerging.

The initial hypothesis was that there would be no difference in I_B between initial spacings after thinning. Because effects between initial spacing and I_B and correlations between prethinning crown dimensions and I_B were not significant for any of the 5 yr after initial thinning, the hypothesis could not be rejected.

Volume and I_V

Total stand volume (V) was significantly influenced by initial spacing before thinning at age 17 yr and 5 yr after thinning ($P \leq 0.017$) (Table 7). Prior to thinning, multiple comparisons between the different initial spacings revealed that V in the closest initial spacing (1.8 x 1.8 m) was only significantly different from the widest initial spacing (3.0 x 3.0 m) and that V was highest in the closest initial spacing. Five yr after thinning, multiple comparisons between the different initial spacings revealed that the two wider initial spacings (2.4 x 2.4 and 3.0 x 3.0 m) were significantly greater in V than the two closer initial spacings (1.8 x 1.8 and 1.8 x 2.4 m). Results showed that more V was produced in plots that were initially at lower stand densities and wider spacings than plots that were initially at higher stand densities and closer spacings.

Prior to thinning, gross volume increment (I_V) was strongly influenced by initial spacing ($P=0.012$) between the ages of 16 and 17 yr (Figure 3). Multiple comparisons between the different initial spacings revealed that the 3.0 x 3.0 m spacing had significantly larger values of I_V than the two closer initial spacings, but was not statistically different than I_V measured in the 2.4 x 2.4 m spacings. Orthogonal polynomial contrasts indicated that the effect of initial spacing at age 16-17 yr was linear ($P=0.002$). Closer spacings produced less I_V and higher total volumes than did wider spacings (Table 7) due to the disproportionately greater number of smaller trees; however, the smaller number of larger trees (Table 3) in the wider initial spacings contributed more to I_V than did closer initial spacings. Stagnation was a possible explanation for this occurrence as the competitive struggle among the trees reduced the combined growth. As a result, the smaller number of larger trees in the wider initial spacings was compensated in volume growth while tree vigor deteriorated in the closer initial spacings.

Table 7. Total stand volume (V) (m^3/ha) for each initial spacing at age 17 yr (before thinning) and age 22 yr (after thinning) for slash pine near Woodworth, LA. Like letters show no significant differences using the Tukey method at the $\alpha = 0.10$ level (degrees of freedom for the error term =12).

Initial Spacing (m)	Age (yr) 17	22
	--------------m^3/ha	--------------
1.8 x 1.8	559a	306a
1.8 x 2.4	475ab	307a
2.4 x 2.4	502ab	384b
3.0 x 3.0	413b	407b
Pr > F	0.017	0.001
SE[a]	27.7125	16.1180

[a] Standard Error

Although slash pine increases rapidly in volume growth and is vigorous at early ages (Lohrey and Kossuth 1990), it is also moderately intolerant of shading and competitors; therefore, growth rates often decrease when stand conditions become shaded or crowded (Langdon and Bennett 1976). Slash pine also has a tendency to stagnate which may eventually lead to uniformity of trees within the stand. It is during this period when trees are weakened; stands develop slowly, and succumb to competition. Since all spacings other than the 3.0 x 3.0

m spacings were delayed in thinning, stagnation could explain part of the inverse relationship between I_V and initial spacing before and after thinning.

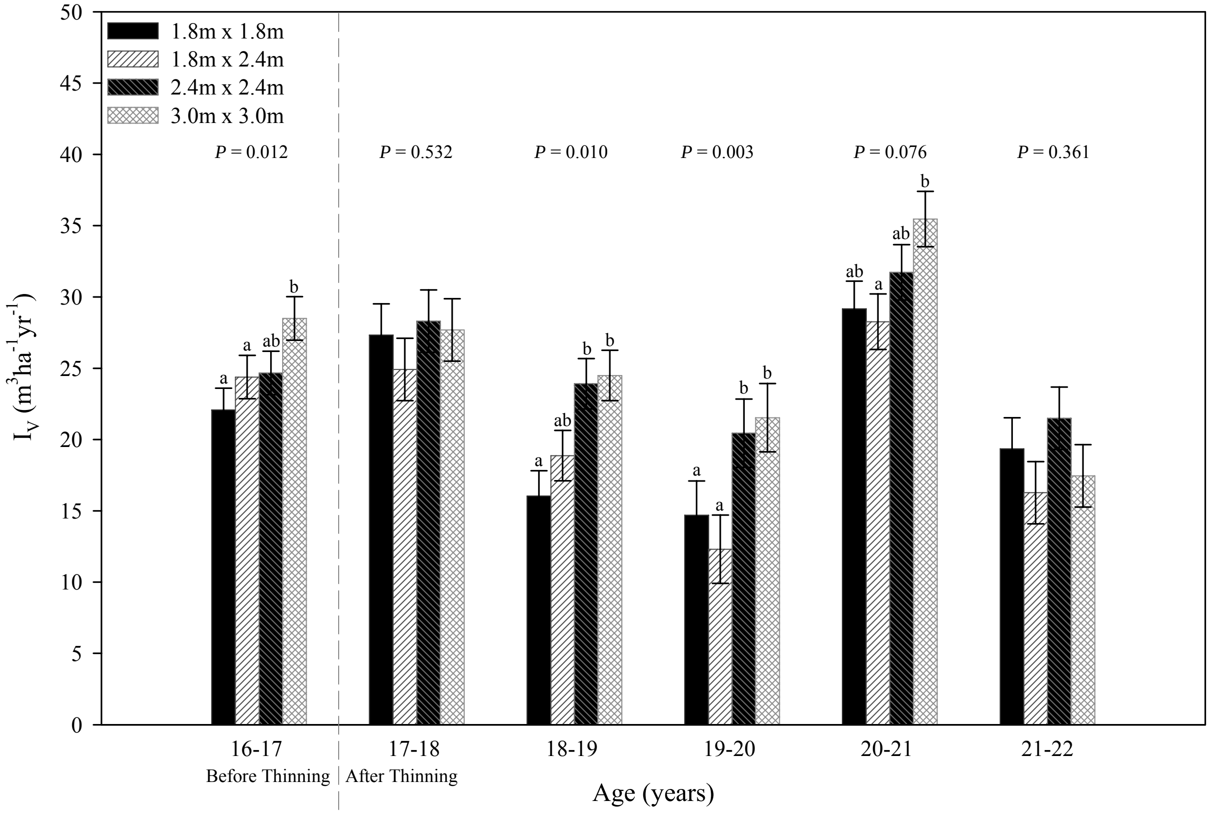

Figure 3. Gross-volume increment (I_V) for each spacing at the growth interval 16-17 yr before thinning and after thinning for growth intervals 17-22 yr for slash pine near Woodworth, LA (n = 20). Like letters show no significant differences using the Tukey method at the α = 0.10 level and vertical bars represent the root mean squared error for each age (degrees of freedom for error = 12).

Initial spacing did not significantly influence I_V at the growth interval 17-18 yr, the first year after thinning (P=0.530) (Figure 3). However, I_V was significantly influenced by initial spacing during the 18-19, 19-20, and 20-21-yr growth intervals (all P≤0.076). Orthogonal polynomial contrasts also indicated linear patterns for those years as well (P=0.003, P=0.002, and P=0.014, respectively). For the 18-19 yr growth interval, multiple comparisons between the different initial spacings revealed that the 1.8 x 1.8 m spacing had significantly less I_V than the two wider initial spacings, but not significantly different from the 1.8 x 2.4 m spacings. The two wider initial spacings were significantly greater than the two closer initial spacings for the 19-20 yr growth interval. During the 20-21 yr growth interval, only the 1.8 x 2.4 and 3.0 x 3.0 m spacings were significantly different from each other and the widest initial spacing had the highest value of I_V. No effects were detected at the 21-22 yr growth interval ($P=0.361$) (Figure 3).

Dean and Baldwin (1996) found that crown properties were generally correlated with I_V as well as mean-tree increment. However, Dean and Baldwin (1996) found that at age 27 yr, these correlations disappeared and lost their associations with stand density and therefore, with canopy structure and growth. The changes in tree vigor that occur during stand development are associated with the ability of the trees to use their growing space (Daniel et al. 1979). Before competition, small trees with smaller crowns have a higher production of stemwood per unit of space occupied or foliage biomass than larger trees with larger crowns (Jack and Long 1992). However, the positive correlations between I_V and prethinning crown dimensions prior to thinning ($P \leq 0.044$) (Table 8) implied that greater I_V was observed on wider-spaced, larger-crowned trees than on closer-spaced, smaller-crowned trees.

After thinning, I_V was positively correlated with prethinning crown size ($P \leq 0.067$) (Table 8) for 3 growth intervals between 18-21 yr with the exception of C_R ($P=0.262$) and C_L ($P=0.103$) at the 19-20 yr growth interval. This indicated a positive correlation between I_V and prethinning crown dimensions where greater I_V was observed in initially wider-spaced trees with larger crowns. This effect became undetectable by the 21-22 yr growth interval ($P>0.669$). Overall, the positive correlation seen between initial spacing and prethinning crown dimensions between 18-21 yr corresponds with significant linear contrasts between I_V and initial stand density revealed in the fixed effects analysis for the same growth intervals (Figure 3).

Table 8. Correlation coefficients relating prethinning crown width (C_W), crown length (C_L), crown ratio (C_R), and crown volume (C_{VOL}) to gross-volume increment (I_V) for the growth interval 16-17 yr before thinning and after thinning for growth intervals 17-22 yr for slash pine near Woodworth, LA.

Crown Variable	Growth Interval (yr)					
	16-17	17-18	18-19	19-20	20-21	21-22
C_W	0.55*	0.18	0.58*	0.42*	0.47*	0.01
C_L	0.48*	0.16	0.57*	0.37	0.49*	0.05
C_R	0.45*	0.30	0.58*	0.26	0.45*	-0.10
C_{VOL}	0.53*	0.18	0.57*	0.42*	0.49*	0.03

*Significant at $\alpha = 0.10$

These results indicate that crown size has a lasting effect after thinning in these slash pine plots. The inverse relationship between initial spacing and I_V suggested that larger trees were already more efficient at I_V than smaller trees prior to thinning. Smaller trees in the closer spacings were under severe competitive stress, had experienced ice damage, particularly in the crowns, and were subject to stagnation. Growth was reduced in these smaller trees and crown recovery was prolonged. Consequently, smaller trees in the closer initial spacings became less capable at producing volume.

The initial hypothesis was that there would be no difference in I_V between initial spacings after thinning. Because the effects between initial spacing and I_V and correlations between prethinning crown dimensions and I_V were significant 3 out of 5 yr after initial thinning, the hypothesis was rejected. This provides evidence that prethinning tree characteristics had an effect on postthinning I_V during the length of this experiment.

Postthinning Stand Development

Harrington (2001b) explained that stands with high stem densities would not be able to fully respond to a thinning treatment because late thinning diminishes C_R and limits or delays responses to thinning. Limitations in growth also exist when live crown ratio is reduced to 40% or less (Smith et al. 1996). Strub and Bredenkamp (1985) found that after thinning, stands with less residual stems per hectare increased SDI quicker when thinned early. In this study, wider spaced stands contained larger trees with larger and more fully developed crowns and were at an advantage at the time of thinning because thinning occurred prior to the onset of intense competition in these plots.

Initial spacing effects on stand density, measured during this study, were examined and results indicated significant differences in SDI at age 16 yr before thinning ($P=0.023$) (Figure 4). Multiple comparisons between the different initial spacings revealed that the widest initial spacing (3.0 x 3.0 m) had significantly smaller values of SDI than the two closer initial spacings (1.8 x 1.8 and 1.8 x 2.4 m), but not the 2.4 x 2.4 m spacing.

After thinning, SDI at age 17 ranged from 383 to 400 SDI (i.e., 35-36% of the maximum SDI) and was not statistically different between the spacings ($P=0.465$) (Figure 4). Significant differences in SDI emerged at age 18 yr as well as an inverse relationship between initial spacing and SDI and continued for the remaining 3 growth intervals (all $P\leq0.008$). Multiple comparisons between the different initial spacings revealed that the two wider initial spacings (2.4 x 2.4 and 3.0 x 3.0 m) were significantly greater in terms of SDI than the two closer initial spacings (1.8 x 1.8 and 1.8 x 2.4 m). These results inferred that postthinning stand development was significantly influenced by initial spacing 2-5 yr after thinning. The inverse relationship between initial spacing and SDI displayed at 2-5 yr after thinning showed that increases in SDI occurred faster in plots that were initially at lower stand densities than plots that were initially at higher stand densities.

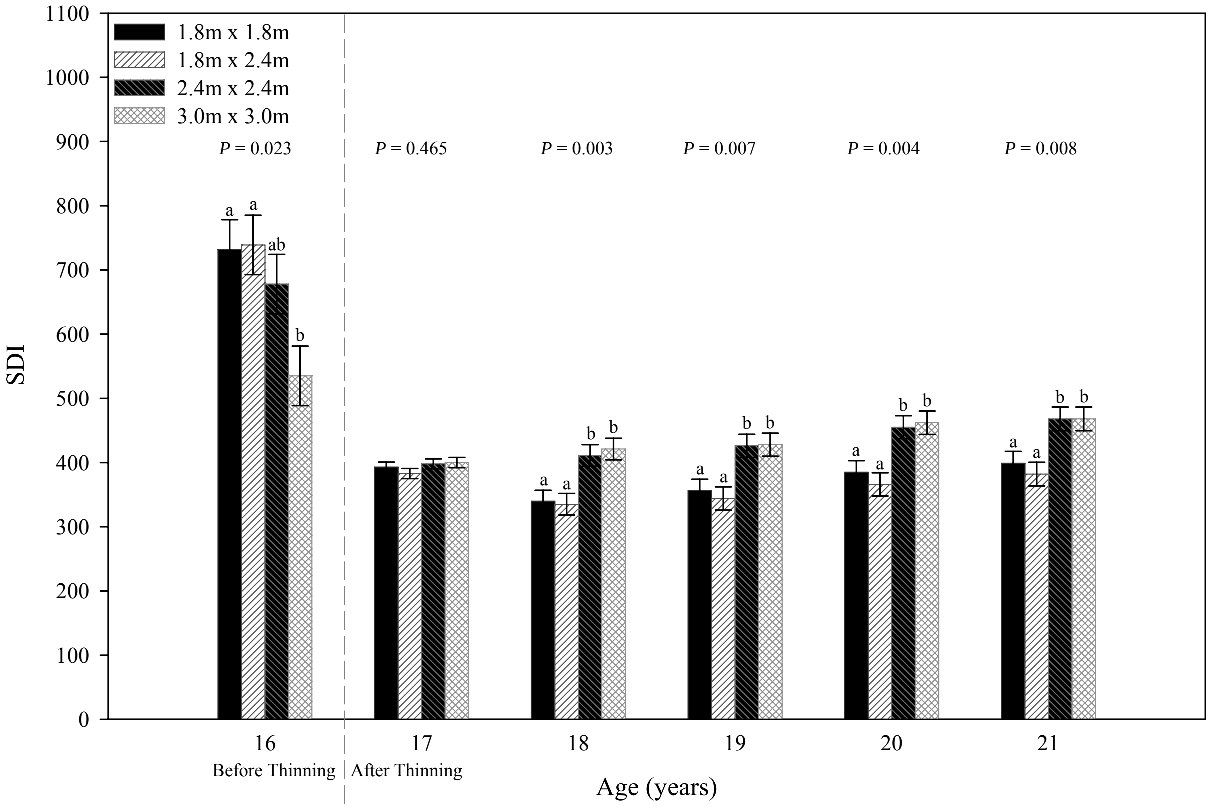

Figure 4. Stand density index (SDI) for each spacing at age 16 yr before thinning and ages 17-21 yr after thinning for slash pine near Woodworth, LA (n = 20). Like letters show no significant differences using the Tukey method at the α = 0.10 level and vertical bars represent the root mean squared error for each age (degrees of freedom for error = 12).

Growth-Growing Stock Relations

How current I_D, I_B, and I_V covaried with the value of percent maximum SDI at the beginning of each of the growth interval was examined with regression analyses before thinning and for each of the 5 yr after thinning. Differences in postharvest growth are expected to show that I_D decreases as stand density increases and that plots with higher stand densities will have larger values of I_B and I_V. The linear model used to relate I_D, I_B, and I_V with SDI was

[5] $Y_i = \beta_0 + \beta_1 \cdot SDI_i + \varepsilon_i$,

where Y_i is the predicted value for the i^{th} observation of I_D, I_B, or I_V, β_0 and β_1 are regression coefficients, SDI is expressed as a % of the maximum, and ε is the random error associated with the i^{th} observation.

Annual diameter increment was significantly and negatively related to stand density prior to thinning ($P<0.001$) (Figure 5a). As expected, I_D decreased with increasing percent maximum SDI from wider-spaced, larger-crowned trees to closer-spaced, smaller-crowned trees. After thinning, no significant relationships between I_D and percent maximum SDI existed (all $P \geq 0.167$) (Figure 5b-f).

Basically, the growth-growing stock relationships between percent maximum SDI and I_D after thinning was primarily due to prethinning stand conditions, especially crown dimensions. The increasingly negative correlation coefficients between I_D and prethinning crown dimensions for the last two growth intervals (Table 4) confirmed that greater I_D was becoming more associated with initially closer-spaced, smaller-crowned trees at lower stand densities 5 yr after thinning. At the same time, stands at initially wider spacings were beginning to experience increasing competition as indicated by their higher values of SDI and, therefore, began to grow slower in diameter. This explains how the relationship between I_D and prethinning crown dimensions may appear unconventional; the discrepancy lies in how the stand densities developed after thinning. Overall, the unexpected inverse relationship observed between prethinning crown dimensions and I_D after thinning was actually created from the relationship between percent maximum SDI and I_D where increasing the stand density, increased I_D.

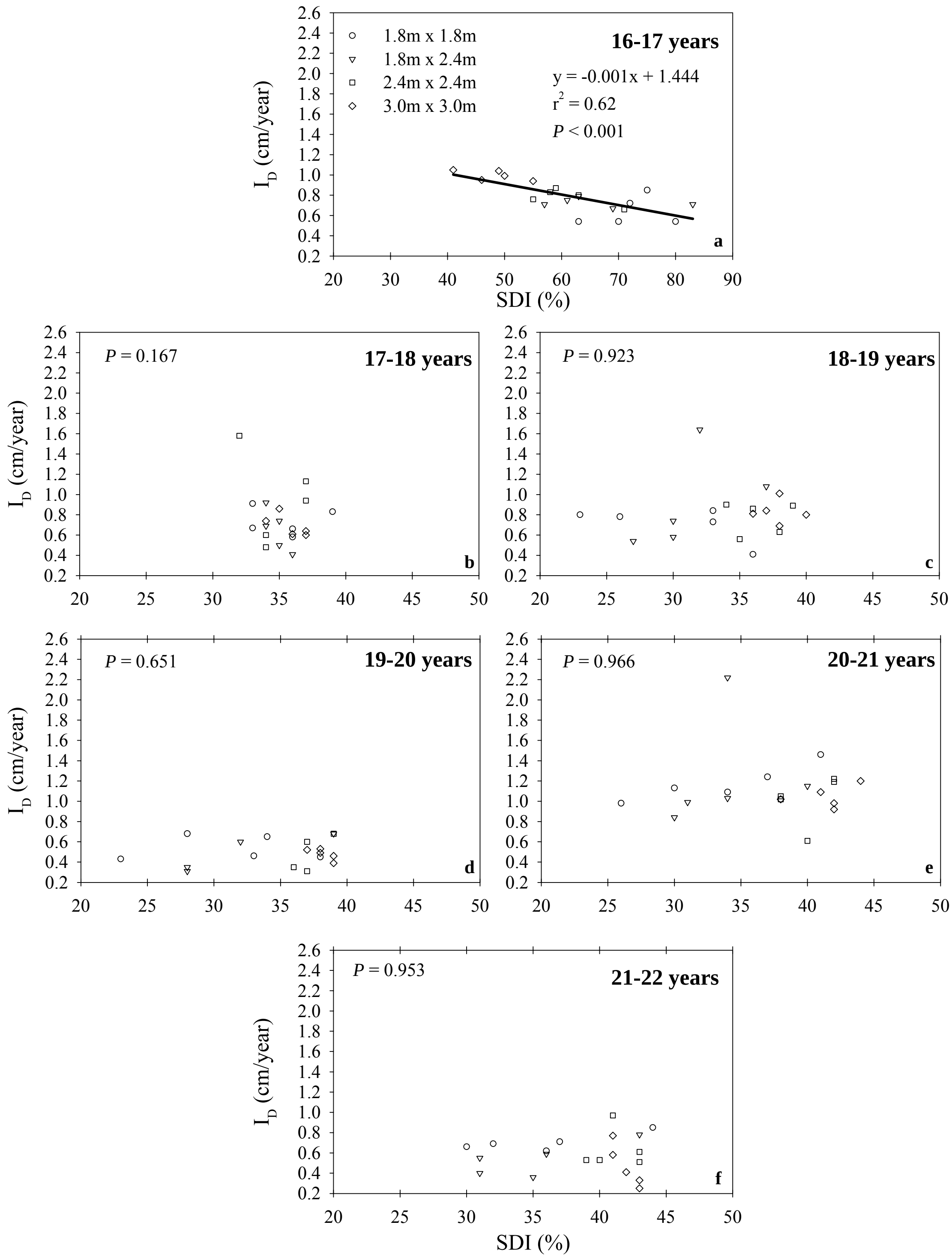

Figure 5. Relationships for the 16-17 yr growth interval before thinning (a) and for the growth intervals 17-22 yr after thinning (b-f) between quadratic mean diameter increment (I_D) and percentage of the maximum stand density index (SDI%) for different initial spacings for slash pine near Woodworth, LA (degrees of freedom for error = 18).

No linear relationship existed between I_B and percent maximum SDI prior to thinning (P=0.241) (Figure 6a) or after thinning (all P≥0.167) (Figure 6b-f). These observations corresponded to the correlation coefficients before thinning and after thinning (Table 6) where no associations were found between prethinning crown dimensions and I_B. The negative correlation coefficients found in the last two growth intervals may be suggestive of some developing association between I_B and percent maximum SDI. However, based on these growth-growing stock relationships before and after thinning for these slash pine stands, no such relationship could be supported.

Stand density was significantly related to I_V before thinning where I_V significantly decreased with increasing percent maximum SDI (P=0.020) from wider-spaced, larger-crowned trees to closer-spaced, smaller-crowned trees (Figure 7a). Interestingly, the typical growth-growing stock relationship was not observed prior to thinning where plots with higher initial stand densities produce more I_V (Curtis et al. 1997). As seen in the fixed-effects analysis, I_V was significantly affected by initial spacing prior to thinning (Figure 3) and surprisingly, greater I_V was observed on wider-spaced, larger-crowned trees than on closer-spaced, smaller-crowned trees (Table 8). These results showed that the prethinning stand conditions concentrated growth onto larger-crowned, more vigorous trees prior to thinning as smaller trees in the closer initial spacings endured greater competition, more extreme ice damage, and maybe stagnation than did the wider initial spacings. This could account for the reduced prethinning growth rates in the plots with higher stand densities.

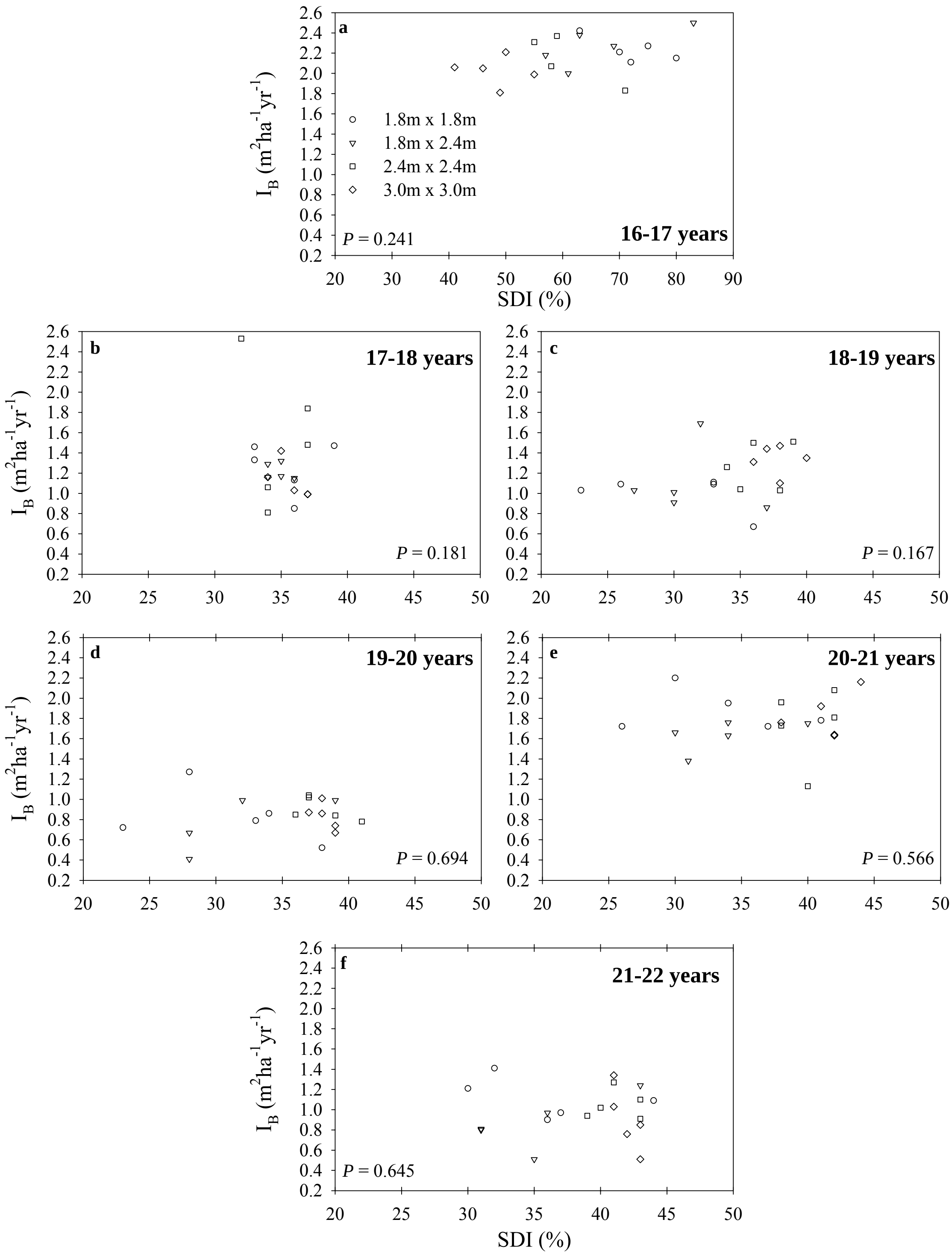

Figure 6. Relationships for the 16-17 yr growth interval before thinning (a) and for the growth intervals 17-22 yr after thinning (b-f) between stand-level basal area increment (I_B) and percentage of the maximum stand density index (SDI%) for different initial spacings for slash pine near Woodworth, LA (degrees of freedom for error = 18).

Typically, V and I_V increase with stand density as well as the growth of individual trees with thinning (Cochran and Barrett 1998, Curtis et al. 1997). After thinning, significant linear relationships between I_V and SDI existed at ages 18, 20, and 21 yr (all $P \leq 0.045$) (Figure 7b-f). These observations corresponded to the correlation coefficients before thinning and after thinning where smaller-crowned, closer-spaced trees were at lower SDIs (Table 8). The usual growth-growing stock relationship occurred where higher I_V was produced in higher density stands, except that in this study, the stands producing higher I_V were initially at wider spacings. The effects of density on prethinning crown dimensions were carried late into stand development allowing the 3.0 x 3.0 m spacings to continue producing higher I_V because they increased in percent maximum SDI quicker than closer initial spacings.

Langsaeter (1941) hypothesized that total volume increases with growing stock until a certain density where increasing the growing stock will reduce volume increment due to extreme competition. Langsaeter's curve as illustrated by Daniel et al. (1979, p. 318) depicts the hypothetical relationship between growth and growing stock apparently showing that volume growth increases with density, plateaus, and declines afterwards as stands become overcrowded. According to the hypothesized relationship by Long (1985), mean tree volume increment increases and is independent of stand density prior to canopy closure and decreases at an accelerating rate afterwards. Dean and Baldwin (1996) found that I_V decreased at an accelerating rate within the self-thinning stage, but contrary to the hypothesized relationship, mean tree growth increased between canopy closure and the self-thinning threshold between ages 22 and 27 yr in loblolly pine plantations. Since all plots were beyond canopy closure and already subjected to self-thinning prior to thinning, mean tree volume growth was dependent upon stand density at the time of thinning and began to decrease quickly. After thinning, wider initial

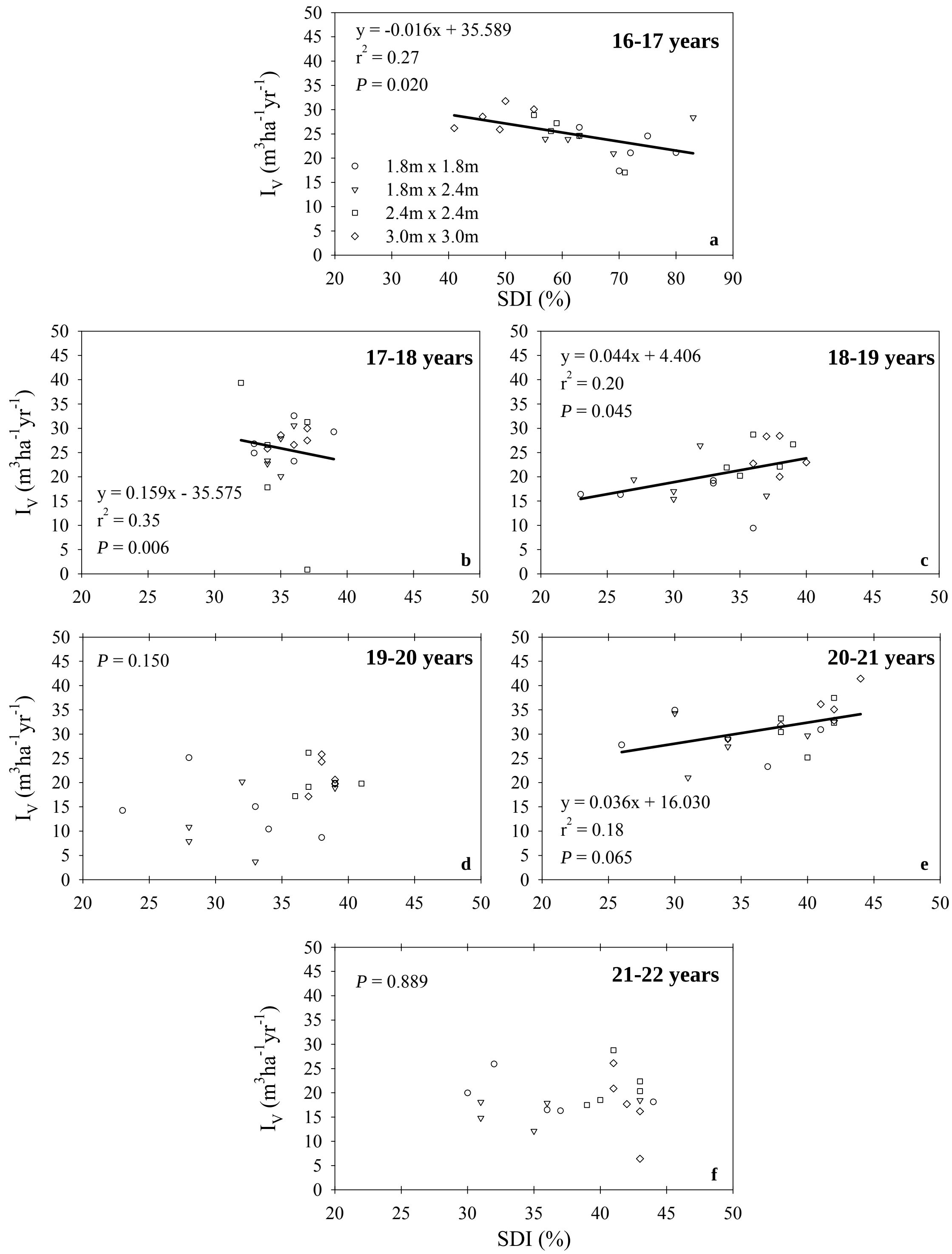

Figure 7. Relationships for the 16-17 yr growth interval before thinning (a) and for the growth intervals 17-22 yr after thinning (b-f) between gross-volume increment (I_V) and percentage of the maximum stand density index (SDI%) for different initial spacings for slash pine near Woodworth, LA. (degrees of freedom for error = 18).

spacings increased quicker in SDI, therefore, increasing in I_V. Carlson and Johnstone (1983) found that growth in stagnated lodgepole pine (*Pinus contorta*) stands eventually decreased at high densities[1]. Both hypothetical relationships by Long (1985) and Langsaeter (1941), as well as competition and stagnation, could presumably give reason for the opposite relationships between I_V and stand density apparent, before and after thinning.

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SUMMARY AND CONCLUSIONS

This study examined the effects of prethinning stand conditions on postthinning growth of slash pine (*Pinus elliottii* var. *elliottii*) plantations in Woodworth, LA before thinning and for five years after thinning. Five replications in a 17 yr old slash pine spacing study were thinned to 35% of the maximum SDI. Plots had been planted at 4 spacings ranging from 1.8 x 1.8 m to 3.0 x 3.0 m and were evaluated to compare the effects on growing stock and stand growth. The primary objective of the study was to determine if postthinning increments in quadratic mean diameter, stand-level basal area, and gross-volume were equal after thinning after thinning to the same density. If any differences occurred, then these differences were related to prethinning stand conditions. Growth was also analyzed in relation to stand density to evaluate postthinning effect on growth-growing stock relationships.

Results from this study indicated that thinning these slash pine plots to a common stand density resulted in no significant differences in postthinning increments of quadratic mean diameter or stand-level basal area between initial spacings. Gross-volume increment was significantly affected by initial spacing between 2 and 4 yr after thinning. During this period, gross-volume increment was higher on initially wider-spaced stands than on initially closer-spaced stands. The wider-spaced stands quickly increased in SDI and also had higher increments in volume; gross-volume increment was positively correlated with SDI expressed as a percentage of the maximum SDI for slash pine during these years.

This study provides useful information about general growth-growing stock relationships and how they are associated to postthinning growth of variously spaced slash pine stands after thinning to a common stand density. Specifically, for the 5-yr period after thinning in these slash pine plots, gross-volume increment increases with stand density while increment in quadratic mean diameter and basal area per ha shows no relationship with stand density. This research may be beneficial when determining forest management strategies for manipulating growth in slash pine plantations.

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