PLANTING DENSITY IMPACTS ON SLASH PINE STAND GROWTH, YIELD, PRODUCT CLASS DISTRIBUTION, AND ECONOMICS

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Abstract—The establishment phase is a very critical decision-making phase in the life of a pine plantation. Key choices in site preparation intensity and type, pre-plant competition control, species selection, seedling genetic quality and size, fertilization, and first year post plant herbaceous weed control have large and long lasting effects on wood yields, rotation length, and products grown. Within a level of forest management, planting density, spacing configuration, and subsequent survival rate can affect stand access, time of canopy closure, time to first pine straw harvest, age to first thinning, number of thinnings, and product class distributions over time. Initially, higher planting densities yield more volume. Eventually, without thinning, stand volumes converge between lower and higher initial stand densities. The more intensive the management and the higher the site productivity the sooner this convergence occurs. An attractive initial spacing for slash pine (*Pinus elliottii* Engelm. var. *elliottii*) may not be so attractive for loblolly pine (*Pinus taeda,* L.) or longleaf (*Pinus palustris,* Mill.). This is due to differences in self-pruning characteristics, branch base diameter, number of branches, branch angle, or potential survival differences by species on certain sites. This paper will discuss the impacts of planting density under different levels of site productivity and management on slash pine stand biology, yields, and economic returns using several long-term studies.

INTRODUCTION

Recent decreases in pine pulpwood demand and stumpage prices to near record lows (TMS 2002) in the southeastern U.S., along with increased demand and prices for pine straw (Doherty and others 2000), has made many forest and land managers re-evaluate initial planting densities. Some forest landowners and foresters are interested in delaying a thinning or forgoing thinning to rake pine straw for a longer period of time. Lower initial densities may help achieve those goals. Conversely, some forest product companies are currently investigating the potential benefits of high initial densities and intensive management for earlier first thinnings, smaller intervals between thinnings, and shorter rotations. The focus of this paper is to discuss the impacts of planting density on stand biology and yields as well as the economic ramifications for stands growing under different levels of site productivity and management.

Choosing a planting density for slash pine (*Pinus elliottii* var. *elliottii*, Engelm.) plantations has important economic and biological ramifications. In slash pine, and conifers in general, increasing planting density decreases tree diameter growth (Ware and Stahelin 1948, Worst 1964, Jones 1987). However, at high stand densities, (greater than 1200 trees per acre), tree height may be suppressed relative to stands planted at wider spacings, but to a lesser extent than is diameter growth (Rahman 1969, Jones 1987). In contrast to the growth of individual trees, total wood production per unit of land area increases as stand density increases because volume associated with the additional trees more than compensates for the decreases in the size of individuals. As stands age, however, convergence of wood production often occurs between different density stands because the growth rate of high density stands reaches a maximum and begins to decline earlier than lower density stands. In addition, greater density dependant mortality in the denser stands may hasten this convergence.

Site productivity, land use history (cut-over, old-field, or pasture), and management intensity have a large influence on how much wood is produced and the timing of growth convergence between different density stands. In general, the faster the growth rate the sooner this growth convergence between different density stands occurs. Some long-term slash pine spacing studies on former old-field sites (Bowling 1987, Jones 1987) have shown that resultant wood yields without thinning were similar by age 20- to 25-years for initial planting densities between 400 to 800 trees per acre (TPA). This rapid convergence of stem production between different density stands on old-field sites may be associated with rapid growth due to low initial hardwood competition, a residual fertilizer effect, and typically good soil tilth.

In contrast, convergence of wood production between different density stands takes longer on cut-over sites due to slower overall growth, but also due to a greater intensity of interspecific competition in the lower density stands. Sarigumba (1984) found that slash pine volume production on cut-over sites planted at 436 TPA was lower than wood volume production of stands planted at 605 TPA by age 25-years on sites of marginal productivity (MAI of 1.25 to 1.70 cords per ac per yr). These sites received low levels of site preparation and management. Borders and Bailey (1985) also found that wood yields on cut-over sites from lower planting densities (400 to 436 TPA) were lower (by 3 to 5 cords per acre) than higher planting densities (800 TPA) through age 25-years. Pienaar and others (1996)

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modeled slash pine planted at two densities on cut-over sites. They predicted that the wood volume production of 400 TPA stands (3300 and 3900 ft^3 per acre) was lower than wood volume production from 800 TPA stands (3850 and 5075 ft^3 per acre) through age 35-years on site index 60 and 70 feet (base age 25-years) sites, respectively.

When considering economic returns related to planting density, however, factors in addition to total wood production need to be considered; timing and intensity of thinning, tree size distribution and resultant product classes, cost of planting, cost of site preparation, potential for pine straw production, and ease of stand access. In two old-field site studies, for instance, planting at lower densities (400 and 436 TPA) resulted in larger diameter, more valuable wood and greater total economic return than the traditional 600 to 800 TPA planting densities under a no thin management regime by age 20- and 25-years (Bowling 1987, Jones 1987).

EFFECT OF PLANTING DENSITY OF INTENSIVELY MANAGED STANDS

Experimental studies have indicated that slash pine yield can be pushed to exceed 3 cords per acre per year with the application of complete control of interspecific competition and fertilization (Borders and Bailey 2001). The incorporation of intensive forest management may impact the relationship between stand density and stem growth, particularly if carrying capacity is altered. To address this question, the Plantation Management Research Cooperative (based at the Warnell School of Forest Resources, The University of Georgia) and its industrial cooperators installed a series of slash pine studies to examine the interaction between stand density and management intensity. Following six growing seasons, the more intensive forest management treatments (complete control of interspecific competition and multiple fertilization) significantly increased tree size. However, the effects of stand density were similar regardless of management intensity (fig. 1). Therefore, the effects of stand density appear to be consistent across a broad range of management intensities and environments.

Although the timing of when convergence in wood production occurs among different density stands is affected by site quality and management intensity, the nearly universal phenomenon of convergence in wood production raises the question as to what resource or biological mechanism limits stem growth as stand density increases. By identifying the limiting processes or resources, these limiting functions hopefully can be addressed through silvicultural inputs, genetic selection, or genetic manipulation. This question was addressed using the intensively managed (multiple fertilizer applications and complete control of interspecific competition) set of Plantation Management Research Cooperative studies discussed above. Given the intensive management and very fast growth rates, stand growth was becoming limited in the higher density stands very early during stand development. For instance, stem growth during the fourth growing season increased only about 3.5 times when planting density was increased five-fold from 300 to 1500 trees per acre (Burkes and others, in press).

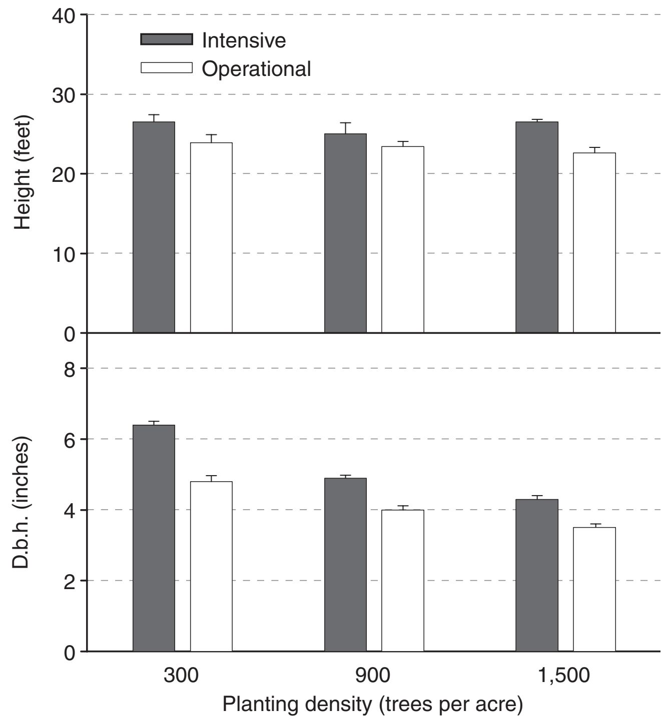

Figure 1—Effect of planting density on the height and diameter of slash pine stands following the sixth growing season. Intensive stands received multiple fertilization and complete interspecific competition control.

One possibility for the limitation of stem growth per unit of land area in the high density stands was that either the ability of foliage to gain carbon through photosynthesis decreased or the rate of carbon loss via respiration increased such that less photosynthate was available for stem growth. However, photosynthetic capacity and respiration rates were not affected by stand density (Will and others 2001). Another possibility was that the slowing of stem growth in higher density stands resulted from more photosynthate being partitioned to root or foliage and less to stem as the competition for above and below ground resources intensified. However, biomass partitioning to stem relative to other stand components did not decrease as stand density increased. Rather, growth efficiency (stem production per unit of leaf biomass) and the ratio between stem growth and standing fine root biomass increased as stand density increased (fig. 2) (Burkes and others, in press), indicating a greater fraction of fixed carbon was used for stem growth at higher stand densities.

What did appear to limit stem growth per unit land area was canopy size, which drives both radiation interception and photosynthetic surface area (fig. 3) (Will and others 2001). The initial greater stem growth rates in denser stands and later slowing of stem growth was well correlated to the development of leaf area. Therefore the limitation in stand growth as planting density increases appears related to a site's capacity to support leaf area which in turn is a function of nutrient and water availability. As a result, silvicultural activities should focus on increasing leaf area.

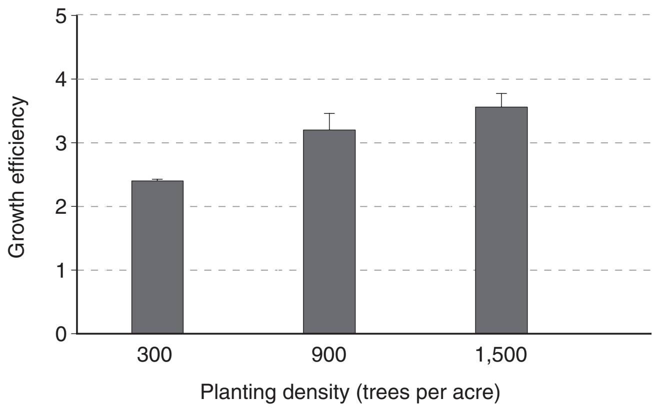

Figure 2—Growth efficiency (stem production per unit of leaf biomass) during the fourth growing season for slash pine stands planted in 1996 at different densities.

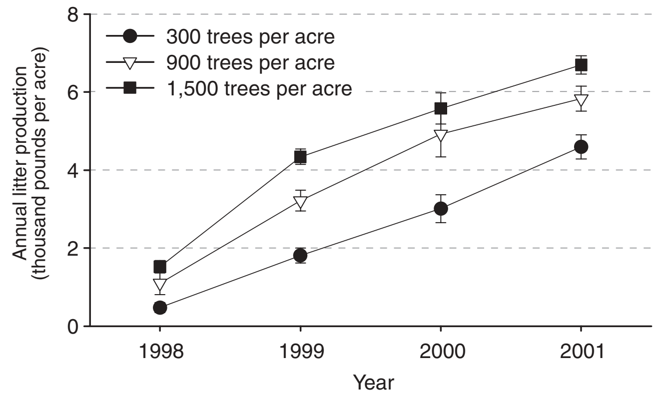

Figure 4—Annual litter production from intensively managed slash pine stands planted in 1996 at different densities. Litter was estimated using traps.

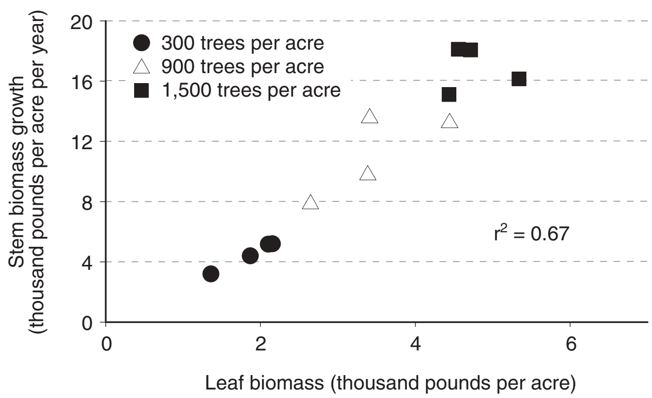

Figure 3—Relationship between leaf biomass and stem biomass growth during the fourth growing season for slash pine stands planted in 1996 at different densities. Leaf biomass was calculated using litter traps. Stem biomass growth was calculated using allometric equations.

Overall, increasing planting density has multiple benefits, including: accelerating early volume production, increasing the efficiency of stem production relative to other stand components, and early site occupancy. The declines in stand growth rate that occur at high stand densities as stand development progresses, combined with economics of stand establishment and product distribution (discussed below), can result in moderate stand densities as the best choice for planting. Higher intitial stocking densities may be financially attractive if aggressive thinning regimes and other silvicultural practices can be employed.

POTENTIAL PINE STRAW PRODUCTION OF INTENSIVELY MANAGED STANDS

Of great interest to some growers of slash pine plantations is the production of pine straw. Intensive forest management, including fertilization and competition control, results in larger canopies and greater potential pine straw production. Intensive management also facilitates pine straw production by keeping the stand clean to maximize rakable area (Morris and others 1992, Dickens 1999, 2001). Overall, intensive forest management results in very high potential pine straw production. Intensively managed stands planted at 1500 TPA produced 380 bales per acre during the sixth growing season (assuming 17.7 lbs per acre) (Morris and others 1992). In comparison, the stands containing 300 TPA (only one-fifth the number of trees) produced approximately 260 bales per acre during the sixth growing season (fig. 4). Canopy closure was realized at age 4-years in the 1500 TPA planting density, at 5-years for the 900 TPA density, and had not yet been reached through age 6-years for the 300 TPA stands. Early canopy closure at the higher initial densities provides forest landowners with pine straw raking income opportunities sooner than the lower initial planting densities. However, pine straw production per tree is greater in the lower density stands and given enough time, pine straw production will be fairly similar among stand densities. Time of first rake, bale per acre production, and number of years of raking are important factors if pine straw production is a high priority**.** In addition to total production, access between rows is an important consideration for pine straw raking operations and should be considered when choosing a planting density.

LONG-TERM EFFECTS OF PLANTING DENSITY FOR SITES WITH LOW TO MODERATE MANAGEMENT INTENSITY AND LOW TO MODERATE SITE PRODUCTIVITY

Several spacing studies were established in the 1950s and 1960s that provide an opportunity to examine the long-term impacts of planting density on stand growth. Since these stands were established in an era before intensive management, they reflect conditions that today would be considered low to moderate productivity.

Effects of Spacing on Low Productivity Sites — Brunswick Pulp and Paper Study

The Brunswick Pulp and Land Company slash pine spacing study was established in 1957 on four Flatwoods soil series on cut-over sites: the moderately well drained Orsino (Spodic Quartzipsamments), somewhat poorly drained Leon (Aeric Alaquods), poorly drained Mascotte (Ultic Alaquods), and poorly drained Pelham (Arenic Paleaquults). Four site preparation levels were applied: burn (control), burn-scalp, burn-bed, and burn-harrow. Four spacings included 6x6 (1210 TPA), 6x12 (605 TPA), 10x10 (436 TPA), and 12x12 feet (302 TPA). The experimental design was split-plot randomized complete block with two replications for each of the four drainage classes. Only pre-plant site preparation was performed with no subsequent weed control, fertilization, or thinning during the 25-year study period.

Merchantable volume (3 inch top outside bark) mean annual increment ranged from 1.0 to 1.7 cords per acre per year (where 86 ft^3 outside bark per cord) during the 25-year study period (Sarigumba 1984, Borders and Bailey 1985). Merchantable volume mean annual increment (MAI) culmination occurred between ages 20 and 25 on all soils but the Pelham. Generally the bed and harrow treatments and 6x6 and 6x12 spacing basal area and volume MAI culminated earlier across the soils than the control and scalp treatments and 10x10 and 12x12 feet spacing.

Age 25-years data from this study for the 6x12 and 10x10 feet spacings are summarized here, assuming that a mixed product class distribution of pulpwood and chip&saw and culmination of merchantable volume MAI are forest management goals. Data from the best site preparation treatment for each soil series were used at age 25-years to calculate stand parameters. These were the bed (Pelham soil) or harrow (Orsino, Leon, and Mascotte) site preparation treatments.

There was little difference in mean percent survival for the 6x12 and 10x10 feet spacing at age 25-years across the four soils. Survival ranged from 76 to 88 percent. Mean d.b.h. for the 10x10 feet spacing was significantly greater than the than the 6x12 spacing on the Leon (difference of 0.9 inch), Mascotte (difference of 0.6 inch), and Pelham (difference of 0.7 inch) soils (table 1). Diameter distributions from the 10x10 spacing produced more trees per acre of the larger diameter classes than the 6x12 spacing (fig. 5). Basal area for the 6x12 spacing was significantly greater than the 10x10 spacing on two of the four soils (table 1). Mean heights for the 6x12 spacing (60 feet) and 10x10 spacing (61 feet) were not significantly different across the four soils at age 25-years.

Merchantable volume (Bailey and others 1982, Borders and Bailey 1985) per acre followed the same pattern as basal area with the 6x12 feet spacing producing significantly greater volume by an average of 4.9 cords after 25-years than the 10x10 spacing. Merchantable volume MAI for the 6x12 spacing was greater than the 10x10 on the Orsino and Mascotte, but was not significantly different on the Leon and Pelham soils through age 25-years (table 1).

The 6x12 spacing produced significantly greater pulpwood volume (5 to 9 inch d.b.h class) than the 10x10 spacing by age 25-years on each soil series (table 1). The 10x10 spacing chip&saw volumes (≥ 9 inch d.b.h class) were not significantly greater than the 6x12 spacing on each individual soil (table 1), but was significantly greater when averaged across the four soils. Using stumpage prices of $20 per cord for pulpwood and $75 per cord for chip&saw (TMS 2000) the 10x10 spacing dollar per acre revenue was 7 percent greater (an average of $109 per acre) than the 6x12 spacing. This per acre value difference is minor and the financial picture may change if a fertilization and thinning regime were employed.

Table 1—Slash pine spacing effects on mean stand parameters at age 25-years on four Georgia flatwoods soils—the Brunswick Pulp and Land Company study

Stand parameter	Soil	Spacing (feet) 6 x 12	10 x 10
		inches	
D.b.h.[a]	Orsino	7.4a	7.6a
	Leon	6.6b	7.5a
	Mascotte	6.6b	7.2a
	Pelham	6.1b	6.8a
		square feet per acre	
Basal area	Orsino	142a	121b
	Leon	112a	107a
	Mascotte	131a	99b
	Pelham	107a	96a
		cords per acre per year	
Merchantable volume[b] MAI	Orsino	1.70a	1.38b
	Leon	1.34a	1.34a
	Mascotte	1.57a	1.19b
	Pelham	1.17a	1.10a
		cords per acre	
Pulpwood volume	Orsino	22.0a	12.9b
	Leon	16.1a	11.3b
	Mascotte	25.5a	12.2b
	Pelham	20.0a	12.8b
Chip&saw volume	Orsino	20.6a	21.5a
	Leon	17.3a	22.3a
	Mascotte	13.9a	17.5a
	Pelham	9.3a	14.8a
		dollars	
Value per acre	Orsino	1,985[c]	1,871
	Leon	1,620	1,899
	Mascotte	1,553	1,557
	Pelham	1,098	1,366

d.b.h. = diameter at breast height; MAI = merchantable volume mean annual increment.

[a] Within a stand parameter and soil treatment means followed by the same letter are not significantly different at the 5-percent alpha level using Duncan's Multiple Range Procedure test.

[b] 86 cubic feet outside bar per cord and 75 cubic feet inside bar per cord are assumed.

[c] Stumpage value based on $20 per cord for pulpwood and $75 per cord for chip&saw (TMS 2000) with a 15-percent defect for chip&saw assumption (PW = 5 to 9 and CNS ≥ 9 inch d.b.h. class).

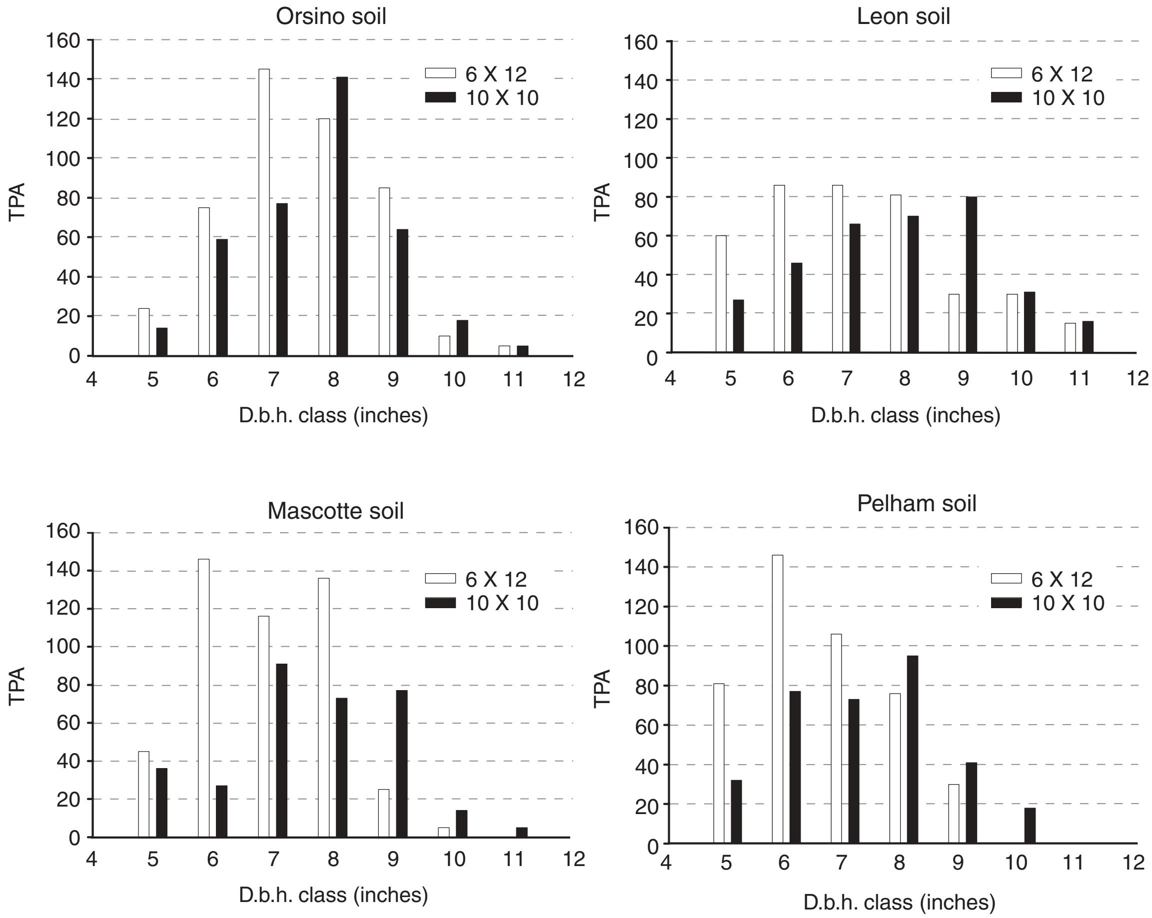

Figure 5—Slash pine diameter distributions by spacing at age 25-years on four Georgia cutover flatwoods soils: Orsino, Leon, Mascotte, and Pelham.

I. Effects of Spacing on Moderately Productive Sites — USFS Dooly County, GA Study

The United States Forest Service (USFS) slash pine spacing study in Dooly County, Georgia was initiated in 1952 on an old-field site. Nursery-grown 1-0 seedlings from the Georgia Forestry Commission nursery in Albany were planted in January 1952, with replanting in March and May 1952 to replace dead seedlings. The soil series represented were Lakeland (sandy Typic Quartipsamments) and Gilead (fine Aquic Halpudults) (Harms and Collins 1965, Jones 1987). Two replications of initial spacings included 6x6 (1,210 TPA), 6x8 (908 TPA), 5x10 (871 TPA), 8x8 (681 TPA), 6x12 (605 TPA), 10x10 (436 TPA), 7.5x15 (387 TPA), and 15x15 feet (194 TPA). The few invading volunteer pines, hardwood, and other woody vegetation were removed from the study area. No fertilizers were applied during the study.

Survival was excellent from study inception, averaging 97 percent by age 4-years (Harms and Collins 1965) and 93 percent at age 12-years. Bennett (1960) noted that by age 5-years, trees were significantly larger in the 10x10 feet and wider spacings than the denser spacings. In this case, Bennett postulated that age 5-years marked the beginning of intraspecific competition for growing space. Harms and Collins (1965) noted that 58 percent of the 6x6 spacing trees reached merchantability compared to 85 percent of the 6x8 spacing by age 12 years old. In subsequent years, a sub-sample of total heights, d.b.h., survival, and live crown ratio were tallied at ages 15-, 20-, 25-, and 30-years (Jones 1987).

This is a brief summary comparing all spacings from age 15- to 30-years. Merchantable volume (4 inch top outside bark) mean annual increment culminated at age 20-years for all initial densities except the widest spacing (15x15 feet), which peaked at age 25 years old (Jones 1987). Merchantable volume MAI at age 20-years ranged from 1.8 cords per acre per year for the 6x6 spacing to 2.10 cords per acre per year for the 6x8 and 8x8 feet spacing. However, merchantable volumes at age 20-years were not significantly different among spacings except that the volume of the 15x15 feet spacing was significantly less than the other spacings (Jones 1987).

Examination of the intermediate spacings (5x10 (871 TPA at planting), 8x8 (681 TPA), 6x12 (605 TPA), and 10x10 (436 TPA), revealed that percent survival was not significantly different among the four spacings at age 20-, 25-, or 30-years (table 2). At age 15-years, the mean d.b.h. for the 10x10 spacing was significantly greater than the three denser spacings. The average d.b.h. of the 6x12 spacing and 8x8 spacing were not significantly different from one

Table 2—Mean stand parameters by spacing and age from the old-field slash pine spacing study in Dooly County, GA

	Age (years)							
Spacing	15	20	25	30	15	20	25	30
feet	- - - - - Arithmetic d.b.h. *(inches)*[a] - - - - -				- - Basal area *(square feet per acre)* - -			
10 x 10	7.3a	8.2a	9.0a	9.7a	111a	134a	141a	136a
6 x 12	6.4b	7.1b	7.9b	8.5b	118a	134a	140a	133a
8 x 8	6.2b	6.9bc	7.6bc	8.1bc	133a	151a	153a	143a
5 x 10	5.6c	6.2c	6.9c	7.5c	133a	147a	148a	134a
	- - - - - - - - - Percent survival - - - - - - - - -				Merchantable volume[b] *(cords per acre)*			
10 x 10	86a	83a	72a	60a	26.7a	40.5a	48.4a	50.0a
6 x 12	85a	77a	66a	55a	26.2a	37.0a	44.6a	46.6a
8 x 8	92a	84a	71a	58a	29.3a	41.8a	48.3a	48.6a
5 x 10	86a	78a	63a	48a	26.8a	38.2a	43.9a	44.2a
	Dominant, codominant total height *(feet)*				- - - - Live crown ratio *(percent)* - - - -			
10 x 10	48a	58a	66a	70a	44a	35a	27a	25a
6 x 12	46ab	55ab	62ab	67ab	42ab	31b	25b	24a
8 x 8	46ab	55ab	62ab	66ab	38bc	30b	23c	22a
5 x 10	45b	53b	60b	64b	36c	31b	24bc	23a

[a] Within an age and stand parameter treatment means followed by the same letter are not significantly different at the 5-percent alpha level using Duncan's Multiple Range Procedure test.
[b] 86 cubic feet outside bar per cord and 75 cubic feet inside bar per cord are assumed.

another, but were significantly greater than the average d.b.h. of the 5x10 spacing (table 2). This d.b.h. trend continued though age 30-years. Diameter distributions at ages 20- and 25-years (fig. 6) illustrate that the 10x10 spacing produced more chip&saw sized trees compared to the higher densities. Basal area per acre of the different spacings was not significantly different between 15- and 30-years and converged by age 30-years. Basal area per acre decreased for all four spacings by 5 to 13 feet^2 per acre between ages 25- and 30-years (table 2) due to increased mortality of the larger diameter trees. Eighteen trees in the > 8 inch d.b.h. classes died between ages 20- and 25- compared to 66 trees between ages 25- and 30-years across the four spacings.

At age 15-years, mean live crown ratio (LCR) followed a similar pattern as d.b.h. among spacings with the greatest LCR's found in the wider spacings (table 2). However, by age 30-years, LCR of all spacings had decreased and was similar among spacings (table 2). An LCR of 33 percent is generally considered the threshold to maintain fast growth rates. The 5x10, 8x8 and 6x12 spacing trees should have

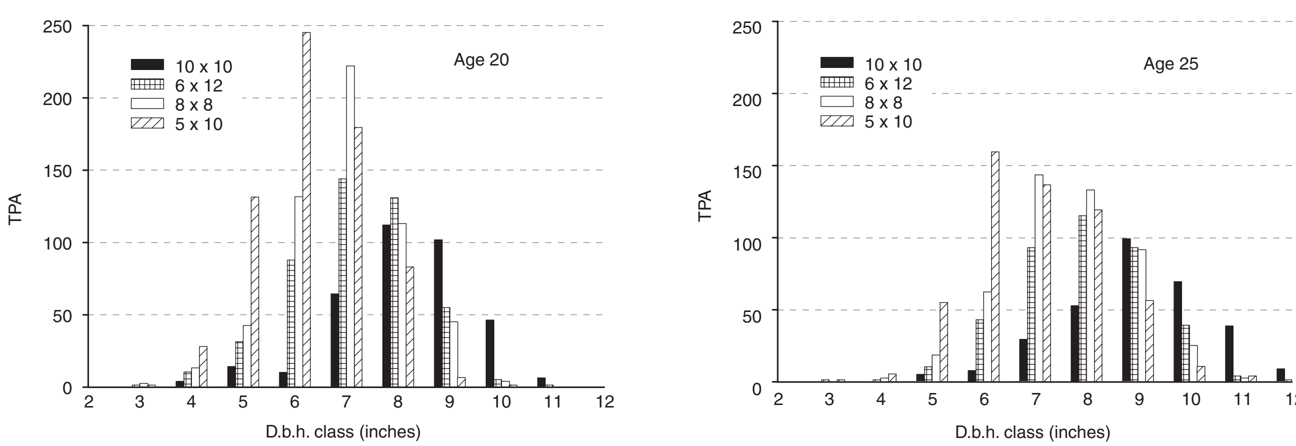

Figure 6—Diameter distributions by spacing and age on the old-field slash pine U.S. Department of Agriculture Forest Service spacing study in Dooly County, GA.

been thinned between age 15- and 20-, while the 10x10 spacing trees thinning could be delayed to maintain LCR greater than 33 percent (table 2) providing a wider thinning window. The mean total height for codominants and dominants was significantly lower in the highest density (5 x 10 feet spacing) compared to trees in the widest spacing (10x10) starting at age 15-years (table 2). This difference was maintained though age 30-years. There were no significant differences in merchantable volume per acre among the four intermediate spacings at age 15-, 20-, 25-, or 30-years (table 2).

II. Effects of Spacing on Moderately Productive Sites — International Paper Study

A slash pine spacing study was initiated by the International Paper Company in 1964. The study area is located in Decatur County, Georgia on an old-field site (Orangeburg soil series - fine-loamy Typic Kandiudults) (Bowling 1987). The study area had six replications of four spacings (400, 600, 800, and 1000 TPA in square configurations), with three of six replications thinned at age 15-years. The study was followed in five year intervals for 20-years (Bowling 1987). Bowling reported that by age 5-years intraspecific competition had not yet occurred as there were no significant differences in mean total height or d.b.h. across the four initial densities. Percent survival ranged from 95 to 98 percent by age 5-years. Basal area per acre was a direct function of surviving TPA (Bowling 1987).

Age 10-years mean d.b.h for the 400 TPA initial density was 0.6, 0.9, and 1.3 inches greater than the 600, 800, and 1000 TPA initial density, respectively, with these differences increasing with stand age (table 3). Basal area peaked in the 800 TPA plots at age 20-years (174 square ft^2 per acre) surpassing the 1000 TPA basal area. The basal area of the 400 TPA and 600 TPA plots were starting to converge with those of the 800 and 1000 TPA plots between ages 15- and 20-years. At age 10-years, mean height increased with decreasing stand density by approximately one foot per two hundred TPA decrease in planting density (table 3). These differences remained fairly stable except for a relative decrease in height increment for the 1000 TPA plot trees at age 20-years. Merchantable volumes were within two cords per acre among the four planting densities by age 10- and 15-years (table 3). By age 20-years, merchantable volume was greatest in the 800 TPA plots (45 cords per acre). The 400 and 600 TPA densities had intermediate volumes (42 cords per acre), while the 1000 TPA had the lowest volume (38 cords per acre).

ECONOMICS OF PLANTING DENSITY UNDER VARIOUS LEVELS OF SITE PRODUCTIVITY

The lower 436 TPA planting density on the relatively low productivity cutover sites (Brunswick Pulp and Land Study) produced 4.9 cords per acre less volume than the 605 TPA planting density. However, the proportion of pulpwood (5 to 9 inch d.b.h. classes) and chip&saw (≥ 9 inch d.b.h. class less a 15 percent defect assumption) varied with density. An average 8.1 cords per acre less pulpwood, but an average 3.7 cords per acre more chip&saw volume were produced at the lower planting density (436 TPA) by age 25-years.

The lower densities (400 and 436 TPA) on the two old-field site study areas (IP and USFS) produced similar merchantable volumes as the higher, traditional planting densities (600 to 605 TPA) during the study periods. However, the lower planting densities (400 to 436 TPA) produced much greater volumes in the chip&saw class, 9 to 13 cords per acre for the IP and USFS studies using a 15 percent defect assumption. Value per acre for the lower planting densities (400 to 436 TPA) was greater than the higher planting

Table 3—Mean stand parameters by spacing and age from the International Paper old-field slash pine spacing study in Decatur County, GA

Planting density	Age (years)							
	5	10	15	20	5	10	15	20
TPA	- - - - - - D.b.h. *(inches)* - - - - -				Basal area *(square feet per acre)*			
400	2.3	6.1	7.6	8.4	12	77	115	144
600	2.3	5.5	6.7	7.3	17	95	136	156
800	2.2	5.2	6.2	6.9	22	112	150	174
1,000	2.1	4.8	5.8	6.4	24	122	154	166
	- - - - Total height *(feet)* - - - -				- - - Merchantable volume[a b] - - -			
400	12	34	53	63	—	10	27	42
600	12	33	51	62	—	10	28	42
800	12	32	51	61	—	9	28	45
1,000	12	31	50	58	—	8	26	38

TPA = trees per acre; d.b.h. = diameter at breast height.
[a] Cords per acre.
[b] Eighty-six cubic feet outside bark per cord and 75 cubic feet inside bark per cord are assumed.
Source: Bowling (1987).

Table 4—Product class distributions and value per acre[a] for the slash pine spacing studies

Study	Age	TPA	PW	CNS	Value
	years		*Cords per acre[b]*		*$ per acre*
BP&LC	25	605	20.9a	15.3a	1,564
		436	12.3b	19.0b	1,673
USFS	20	871	37.2a	0.74b	800
		681	37.5a	3.4b	1,002
		605	31.2a	4.9b	989
		436	21.6b	14.8a	1,540
	25	871	35.5a	6.2c	1,174
		681	33.2a	11.1bc	1,498
		605	26.3b	13.8b	1,558
		436	14.3c	26.9a	2,302
	30	871	28.2a	11.7c	1,439
		681	26.4a	16.7bc	1,776
		605	21.4b	21.4b	2,035
		436	11.1c	30.8a	2,535
IP	20	1,000	30	8	1,200
		800	31.5	13.5	1,643
		600	27	15	1,665
		400	17.5	24.5	2,188

TPA = initial planting density per acre; PW = pulpwood; CNS = chip&saw; BP&LC = Brunswick Pulp and Land Company; USFS = U.S. Department of Agriculture Forest Service; IP = International Paper Company.

[a] At $20 per cord pulpwood and $75 per cord chip&saw (TMS 2000) and a 15-percent chip&saw defect assumption.

[b] Within a study, age and product class treatment means followed by the same letter are not significantly different at the 5-percent alpha level using Duncan's Multiple Range Procedure test.

densities (600 or greater TPA) on the two old-field sites discussed here (table 4).

Value per acre increases associated with the lower planting densities ranged from $109 (7 percent gain) on the relatively low productivity cutover sites, $500 to $750 (25 to 92 percent gain) on the USFS old-field study area, and $500 to $900 per acre (31 to 75 percent gain) on the IP old-field site (table 4). Because there was a greater total volume production in the higher density stand on the cutover site and similar volumes on the old-field sites, the greater value of the lower density stands resulted from the large price disparity between pulpwood and chip&saw. Therefore, for all three long-term studies, the value per acre was higher at the lower planting density.

The best planting density can depend largely on future product prices as well as landowners needs and objectives. If the price disparity between pine pulpwood and chip&saw continues to be large, then the combination of maximizing wood volume production, product class distribution to favor higher valued products, and wood quality will be high priorities. Maximizing wood volume alone may not be as high a priority that is once was in the mid-1990s when pulpwood prices reached all time highs (TMS 1998).

DISCUSSION

Forest landowners, practicing foresters, and land managers should address the following when choosing a spacing for slash pine plantations: (1) rotation age, (2) products grown (pulpwood, chip&saw, sawtimber, poles, pine straw), (3) product prices, (4) thinning timing, number, and intensity, and (5) equipment access needs. In addition, the intensity of forest management also must be considered since growth within a planting density can be dramatically affected by activities such as site preparation, competition control, and fertilization.

Higher density plantings achieve canopy closure, site utilization, and pine straw production earlier than lower density plantings under the same level of management. An early first thinning (as early as age 8- to 10-years-old assuming the removed stems are merchantable) may be warranted to maintain stand vigor, diameter growth, and volume production in the intensively managed higher density stands. Generally stands are operationally thinned later, between ages 12- to 18-years or when average total tree height is at least 40 feet. The higher planting densities thinning window to optimize growth rates are narrower than for the lower planting densities. Higher planting densities also may be beneficial on cut-over sites with low site preparation and management inputs. The higher planting densities help crop trees occupy the site, whereas the lower planting densities may permit high interspecific competition until much later during stand development, reducing early stand volume production.

In contrast, for those forest landowners whose objective is delaying or forgoing a thinning, raking pine straw as long as possible, and growing mostly chip&saw and larger sized wood, lower planting densities may be the best choice. A disadvantage though is a time delay in canopy closure with lower planting densities, increasing the time to first pine straw revenue. The lower planting densities (400 and 436 TPA) produced the same or greater volume as the higher planting densities (600 to 800 TPA) by age 20-years and much more chip&saw volume on the two old-field sites (IP and USFS studies). Excellent pre- and early post-establishment competition control to maximize survival, growth, and site occupancy should be a high priority for lower density stands. In addition, stand access for ground equipment will often dictate row width and depends on equipment size and operator experience.

LITERATURE CITED

Bailey, R.L.; Pienaar, L.V.; Shiver, B.D; Rheney, J.W. 1982. Stand structure and yield of site prepared slash pine plantations. UGA College of Ag. Exp. Stn. Res. Bull. 291. 83 p.

Bennett, F.A. 1960. Spacing and early growth of planted slash pine. Journal of Forestry Vol. 58: 966-967.

Borders, B.E.; Bailey, R.L. 1985. Stand density effects in slash and loblolly pine plantations. PMRC res. Paper. 1985-1. 149 p.

Borders, B.E.; Bailey, R.L. 2001. Loblolly pine: pushing the limits of growth. South. J. Appl. For. 25: 69-74.

Bowling, D. 1987. Twenty year slash pine spacing study: what to optimize? In: Proceedings of the 4th Biennial So. Silvi. Res. Conf., Atlanta, GA. Nov 406, 1986. SRS GTR SE-42. pp. 300-304.

Burkes, E.C.; Will, R.E.; Barron, G.A. [and others]. [In press]. Biomass partitioning and growth efficiency of intensively managed *Pinus taeda* and *Pinus elliottii* stands of different planting densities. Forest Science.

Dickens, E.D. 1999. Effect of inorganic and organic fertilization on longleaf pine tree growth and pine straw production. In: Proceedings of the 10th Biennial So. Silvi. Res. Conf. Shreveport, LA, February 16-18, 1999. USDA Forest Service GTR SRS-30. Pp. 464-468.

Dickens, E.D. 2001. Fertilization options for longleaf pine stands on marginal soils with economic implications. In: Proceedings of the 31st Annual So. Forest Econ. Workshop. March 27-28, 2001. Pp. 67-72.

Doherty, B.A.; Teasley, R.J.; McKissick, J.C.; Givan, B. 2000. Nineteen ninety-nine farmgate value report. UGA CAES Center for Agribusiness and Econ. Dev., Center Staff Report No. 6. Athens, GA 160 p.

Harms, W.R.; Collins, A.B. 1965. Spacing and twelve-year growth of slash pine. Journal of Forestry. Vol. 63: 909-912.

Harms, W.R.; DeBell, D.S.; Whitsell, C.D. 1994. Stand and tree characteristics and stockability in *Pinus taeda* plantations in Hawaii and South Carolina. Canadian Journal of Forest Research. 24: 511-521.

Jones, E.P. 1987. Slash pine plantation study – age 30. Proceedings of the Fourth Biennial Southern Silviculture Conference. USDA Forest Service Gen. Tech. Rep. SE-42. pp. 45-49.

Mann, W.F.; Dell, T.R. 1971. Yields of 17-year-old loblolly pine planted on a cutover site at various spacings. USDA Forest Service Research Paper SO-70. 9 p.

May, J.T.; Rahman, S.; Worst, R.H. 1973. Effects of site preparation and spacing on planted slash pine. J. of For. 71: 333-335.

Morris, L.A.; Jokela, E.J.; O'Connor, J.B., Jr. 1992. Silvicultural guidelines for pine straw management in the southeastern United States. Georgia Forest Res. Paper. #88, Georgia Forestry Commission, Macon, GA. 11 p.

Rahman, S. 1969. Effects of site preparation and spacing on planted slash pine. MS Thesis. UGA. 41 p.

Ross, S.M.; McKee, W.H., Jr.; Mims, M. 1995. Loblolly and longeaf pine responses to litter raking, prescribe burning, and fertilization. In: Proceedings of the 8th Biennial So. Silvi. Res. Conf. Auburn, AL. Nov. 1-3, 1994. Pp. 220-224.

Sarigumba, T.I. 1984. Sustained response of planted slash pine to spacing and site preparation. In: Proceedings of the 3rd Biennial So. Silvi. Res. Conf. USDA Forest Service. So Exp. Stn. Gen. Tech. Rep. SO-34, pp. 79-84.

Sarigumba, T.I.; Anderson, G.A. 1979. Response of slash pine to different spacings and site preparation treatments. SJAF 3: 91-94.

TMS. 1998. Timber Mart South stumpage prices – 2nd qrtr for south GA 1998. Warnell School of Forest Resources. UGA, Athens, GA.

TMS. 2000. Timber Mart South stumpage prices – 2nd qrtr for south GA 2000. Warnell School of Forest Resources. UGA, Athens, GA.

Ware, L.M.; Stahelin, R. 1948. Growth of southern pine plantations at various spacings. Journal of Forestry. 46: 267-274.

Will, R.E.; Barron, G.A.; Burkes, E.C. [and others]. 2001. Relationship between intercepted radiation, net photosynthesis, respiration, and stem volume growth of *Pinus taeda* and *Pinus elliottii* stands of different densities. Forest Ecology and Management. 154: 155-163.

Worst, R.H. 1964. A study of effects of site preparation and spacing on planted slash pine in the Coastal Plain of southeast Georgia. Journal of Forestry 62: 556-560.