A Review of Thinning for Slash and Loblolly Pine in the South.

PLANTATION MANAGEMENT RESEARCH COOPERATIVE

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A Review of Thinning for
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Introduction

The concept of thinning had its roots in early European forestry with the term being coined by G. L. Hartig in 1791 (Kostler 1956). There are several references that describe the historical development of this silvicultural technique (Fernow 1913, Braathe 1957) which was defined by Braathe (1957) as:

"the act of removing some of the stems in an immature stand of trees in order to give the remaining trees better conditions for growing and producing wood of high quality."

Thinning in the southern United States is an outcome of the development of forestry in this region. The virgin forest of the Southeast was initially cut by settlers as they established pasture and cropland during their inland migration from the coast and by early lumber companies practicing the then popular "cut out and get out" approach to forestry. Colonization and cutting continued until its peak around 1920. It was during the agricultural depression of the 1920's and the onset of the great economic depression of the 1930's that large areas of farmland and cutover stands were abandoned. The South's second forest developed primarily through natural regeneration of these abandoned areas although some planting by groups such as the Civilian Conservation Corps did occur on some badly eroded sites. Spurred by the need to manage many overly dense stands to supply fiber to the quickly expanding pulp and paper industry, thinning became an integral part of southern forest management. Following World War II the forest industry grew rapidly and artificial regeneration became the primary reforestation technique. It was during this era that emphasis moved more heavily toward managing initial stand density during planting than relying
upon thinning to accomplish this later. Many spacing trials were established throughout the South during this period.

Early publications on thinning of southern pines dealt with rules or guidelines that recommended a desired spacing based on the relationship between stand density, in terms of trees per acre, and the average diameter of the stand. The D-plus rule was very popular in southern silviculture in the mid to late 1940's. This method was an attempt to simplify the thinning procedure to adjust ground spacing between trees to maximize subsequent growth. Mitchell (1943) advocated the D+6 rule for managing southern pine woodlots. Mulloy (1946) upon review of the D+ rules suggested that "no uniform addition can be made to the diameter to determine spacing." Another method prevalent during this period included a stand density index approach (Reineke 1933, MacKinney and Chaiken 1935). Both articles defined equations to predict the logarithm of the number of trees per acre for fully stocked stands as a function of the average stand diameter. Another concept used as a thinning guide was to express stand spacing as a percentage of the dominant height of the stand (Gevorkiantz 1947, Wilson 1946). Their premise was that the ratio of spacing to height at full stocking had limited variance and was for practical purposes, constant. It was not until 1949 that the relationship between stand basal area and average dbh was used as a guide in thinning (Stahelin 1949). Stahelin noted that the logarithmic curves presented by Reineke (1933) and MacKinney and Chaiken (1935) failed to model the asymptotic nature of basal area in older or larger diameter stands.

During the 1960's and 70's many initial reports were published dealing with the effects of thinning on southern pines. Most reports were based on early spacing trials or plots thinned to specific basal areas and their effects on stand diameter, height, and volume increment. Many reported empirical results while fewer developed stand prediction equations for whole stand parameters. The following is an attempt to summarize the available literature on the effects of thinning on slash and loblolly pine in the South. This review is presented by stand attribute rather than by individual thinning experiment.
Effects of Thinning on Stand Diameter

2.1 Average Diameter and Diameter Increment

Literature regarding the effects of thinning on average stand diameter and periodic diameter increment are a mixture of initial spacing trials, basal area reductions, multiple thinning schedules, and a combination of these treatments. In general, average stand diameter increases inversely with residual stand density, whether in terms of residual trees per acre or residual basal area. In dense naturally seeded stands of slash pine in the lower coastal plain of South Carolina thinned at age 3 to densities between 1,012 and 16,188 trees per acre, Harms and Langdon (1976) reported that differences in mean diameter were evident by age 8. By age 14, plots thinned to 1,012 trees per acre averaged 4.5 inches while those thinned to 16,188 trees per acre averaged only 2.6 inches. From age 10 to 14 the increase in mean diameter was curvilinear, increasing inversely with initial stand density (trees per acre). Similar results were reported for naturally seeded slash pine in Florida (Cooper 1955) and Georgia (Collins 1967), natural loblolly stands in southern Arkansas pre-commercially thinned at age 3 (Grano 1969) and age 15 (Bower 1965), and in direct seeded loblolly stands in central Louisiana (Lohrey 1972, 1977). Following a review of 25 years of pre-commercial thinning of southern pines, Mann and Lohrey (1974) suggested:

1) all stands in excess of 5,000 trees per acre should be thinned.

2) dense stands should be thinned around age 3 to 500 to 750 trees per acre to insure rapid diameter growth without reducing volume growth.
3) thinning in swaths was as effective as selection thinning and less expensive.

With densities more common to operationally managed plantations, mean stand diameter also increases inversely with stand density. Initial trials with old-field slash pine plantations located on the George Walton Experimental Forest in Georgia indicated that the relationship between mean stand diameter and stand density was linear through age eight (Bennett 1960b). Working with the same stands, Harms and Collins (1965) reported that the linear decrease noted by Bennett became curvilinear beginning at age 8 and intensified through age 12. Dell and Collicott (1968) working with old-field slash pine in the middle coastal plain of Georgia noted that stands thinned at age 12 and 13 to residual basal areas between 50 and 125 square feet, exhibited a similar decrease in average stand diameter with increasing residual basal area three years after thinning. Periodic diameter increment has also been shown to increase inversely with stand density but exhibits a reduction with time. In natural loblolly stands in Louisiana repeatedly thinned from age 17 to 35, Chapman (1953) reported that periodic diameter increment increased inversely with density with the greatest ten-year periodic diameter increase of 3.59 inches at approximately 200 stems per acre (15 foot spacing treatment) which was 1.01 inches larger than the unthinned plots. Considering only the largest 100 trees, periodic diameter increment was 3.7 inches for the most heavily thinned plots. All thinned plots averaged approximately 0.5 inch larger than unthinned plots. Mann (1952), also working with loblolly pine in Louisiana (Maxwell Thinning Study), found similar results. Stands in this study were initially thinned at age 8 to 18 and periodically thinned at 5 and 10 year intervals. To age 33, the heaviest thinned plots had 5-year diameter growth rates that equalled or exceeded the growth rates exhibited by the unthinned and
lightly thinned treatments. From age 33 to 45, the unthinned and lightly thinned treatments showed the largest diameter growth. In southwest Louisiana, Feduccia and Mann (1976) developed periodic diameter growth equations for loblolly pine planted at a variety of spacings and thinned at age 17 to residual basal areas ranging from 60 to 120 square feet. The equations are linear functions of density (trees per acre) at the beginning of the growth period. The effect of residual density was greater for all merchantable trees than for the 50 largest trees per acre. Diameter growth rates of 3 inches in 10 years were only evident for the largest 50 trees per acre in stands having no more than 250 stems per acre. The authors also found that diameter growth increased directly with site index and inversely with basal area. This same relationship was evident in slash pine stands on medium to poor sites in west central Louisiana (Feduccia 1977). Stands were 14 and 16 years old and thinned with 5-year thinning schedules to residual basal areas ranging from 40 to 130 square feet. For residual densities between 40 and 70 square feet, an increase of site index of 10 feet resulted in a 10-year increase in diameter of 0.5 inch and a reduction in dbh of 0.31 inch for each 10 ft² increase in basal area. For residual basal areas between 70 and 100 square feet, the incremental reduction in diameter was 0.20 inch for each 10 ft² increase in basal area and a reduction of 0.10 inch for residual basal areas over 100 square feet. The decrease in diameter was less when considering only the 60 largest trees per acre. Linear periodic annual diameter growth equations were developed as functions of site index, age and basal area. Separate equations were presented for all trees and for the largest 60 trees per acre.

Results of ten-year growth of planted slash pine in the flatwoods region of the West Gulf Coastal Plain initially thinned at age 17 to varying basal area treatments (Enghardt and Mann 1972) showed that differences in periodic annual diameter growth increased inversely with residual basal area. Periodic annual diameter growth ranged from 0.28 inch for
stands cut to 70 square feet of basal area to 0.20 inch for unthinned plots. Heavy thinnings to 70 ft² increased diameter growth 0.06 inch more than plots thinned lightly to 100 square feet, or an average of 0.03 inch for each 15 square feet of residual basal area. Plots thinned to at least 85 square feet of basal area exhibited an increase in diameter growth for the second 5-year growth period. No statistical difference was found between plots thinned to 100 square feet and unthinned plots during this 10 year study. Feduccia (1979) reported on the same thinning treatments for older slash pine stands in this region but remeasured through age 37. Average dbh ranged from 9.8 inches on the unthinned check plots to 13.3 inches on plots most heavily thinned at age 27. Diameter growth during the 20-year period exhibited an overall increase with decreasing residual basal area through age 27 and then decreased during the next 10-year period. Between ages 27 to 32, diameter growth decreased at an average rate of 0.04 inch per year for each 15 ft² increase in residual basal area within the range of 55 to 115 square feet. During the last 5-year growth period (ages 32 through 37), diameter growth declined at an average rate of 0.03 inch per 15 ft² increase in residual basal area. Twenty-year periodic diameter growth was largest (0.28 inch) for the most heavily thinned plots and least (0.14 inch) for the unthinned check plots. The effect of stand age on thinning of slash pine to several residual basal areas was reported by Mann and Enghardt (1972) for a cutover site in central Louisiana. Plots were thinned at age 10, 13 and 16 to residual basal areas of 70, 85 and 100 square feet. Results indicate:

"For the 9-year period, diameter growth was best on plots thinned heavily at age 10, averaging 0.30 inch annually. It was progressively lower as thinning was deferred and residual basal areas were higher. For all residual basal areas combined, delay of the first thinning to age 13 reduced diameter growth by about 7 percent, and a 6-year delay
reduced it by 22 percent. Differences between light and heavy thinning averaged about 18 percent for all times of first thinning. As expected, differences due to stocking levels decreased as the first thinning was delayed. Growth on the check plots averaged 0.18 inch annually, or 40 percent less than on plots thinned heavily at age 10."

Diameter growth on the largest 50 trees per acre was less pronounced but followed the same trends found for all trees, with the exception that thinning intensity did not affect diameter growth during the 10 to 13 year age period. "Thinned stands outgrew unthinned ones, regardless of the age of first thinning."

2.2 Diameter Distributions

Although average diameter data is informative, diameter distributions provide the land manager with a clearer picture of the development of stands following thinning. It is the number of trees in each diameter class that permits valuation by product class. In heavily stocked stands of direct seeded loblolly pine in central Louisiana that were pre-commercially thinned at age 3, plots thinned to 750 trees per acre had the greatest percentage of stems larger than 6 inches dbh (27% more) while unthinned check plots had the fewest at age 16 (Lohrey 1977). The number of trees greater than 6 inches was inversely related to the number of residual stems per acre at age 3. However, differences between treatments disappeared when the threshold diameter limit was reduced to 4 or 5 inches. In planted loblolly stands in southwest Louisiana thinned at age 17 and remeasured at age 22, diameter distributions were found to be influenced most by planting density (Feduccia and Mann 1976). Results of this study indicate that the number of trees greater than 10 inches dbh increased with wider spacings and site index while decreasing
with increasing residual basal area. For stands of site index 90 (base age 25) thinned to 60 square feet of basal area, the 12 X 12 foot spacing treatment had 72% of the residual stems larger than 10 inches dbh. The unthinned check plots for this spacing treatment had only 55% of the residual stems in this class. In the 9 X 9 foot spacing treatment thinned to the same residual density, the thinned stands contained only 36% and unthinned stands 24% of the residual stems larger than 10 inches dbh. The effect of multiple thinnings on diameter distributions of older loblolly pine stands in this same area was reported by Mann and Feduccia (1976). These stands, originally planted at 10 X 10 foot spacings, were initially thinned to 70, 85, and 100 square feet of basal area per acre at age 20 and thinned every five years to age 45. The number of trees at least 10 inches dbh at age 30 was largest in the most heavily thinned treatments (79.4%) though differences between treatments were small. Unthinned check plots contained only 56.1% of trees in this size class. The authors noted that differences between thinning treatments and between thinned and unthinned stands decreased as stands became older than 35 years of age. In the same study, slash pine stands initially planted at 6 X 7 foot spacings were thinned from below at age 17 with repeated thinnings to the same residual densities at 5-year intervals. At age 32, the percentage of trees at least 10 inches dbh was greatest for stands thinned to 70 square feet of basal area per acre (84.1%). Stands thinned to 85 and 100 square feet contained 67.8 and 59.8 percent, respectively. Unthinned check plots contained only 32.8% of the stems in this size class. Similar results were reported by Feduccia (1979) for thinned slash pine plantations in the West Gulf area of southwest Louisiana. Less dramatic differences were reported by Enghardt and Mann (1972) for slash pine stands planted at 6 X 7 foot spacings. At age 27 stands thinned to 70 square feet had 41.9% of the trees greater than or equal to 10 inches dbh while unthinned check plots contained only 16.4%. In general, all thinning treatments increased the proportion of
larger sized trees and the increase was directly related to thinning intensity. The effect of thinning intensity on diameter distributions for slash pine on poorer sites was reported by Feduccia (1977). These stands were located in west central Louisiana and planted on a 6 X 8 foot spacing with site indices ranging from 60 to 87 feet (base age 50). Stands were initially thinned at age 14 to 16 to residual densities of 40 to 130 square feet of basal area. Stands were repeatedly thinned at 5-year intervals. Although the number of trees that were at least 10 inches dbh increased inversely with thinning intensity, differences between thinning treatments and with the unthinned check plots were much smaller than for the studies previously discussed. At age 25 only 6.5 percent of the trees for stands thinned to 70 square feet were in this size class while unthinned check plots contained only 3.4 percent. It would appear that thinning is less effective in producing larger trees on poorer sites and that the effect of differences in residual density on tree size is less pronounced.

The effect of age at initial thinning was explored by Mann and Enghardt (1972) with slash pine stands planted at 6 X 7 foot spacings in Louisiana. Stands were initially thinned at ages 10, 13 and 16 to residual basal areas of 70, 85 and 100 square feet. Thinnings were repeated at 3-year intervals and treatments compared at age 19. Though the results were not conclusive, stands initially thinned at age 10 had twice the number of stems in the 9 and 10 inch classes than those stands initially thinned at age 16. The unthinned check plots contained fewer 9 and 10 inch trees than stands initially thinned at age 10 and 13 but equalled those initially thinned at age 16. As reported in all previous studies mentioned, the difference between thinned and unthinned treatments was reduced as the threshold diameter limit decreased. When considering all trees greater than or equal to 7 inches dbh, the unthinned treatments contained more trees in this size class than did any thinning treatment.
2.3 Diameter Distribution Models in Thinned Stands

The Weibull distribution function has been widely used to characterize diameter distributions in unthinned stands since its introduction by Bailey and Dell (1973). In a test to determine if this model could adequately characterize repeatedly thinned stands of old-field slash pine, Bailey et al. (1981) reported that after-thinning data fitted the Weibull model as well as before-thinning data. They presented both after-thinning prediction and projection equations for the 24th, 63rd and 93rd percentiles. A percentile based parameter recovery procedure was employed to recover the Weibull parameters. Strub et al. (1981) suggested a procedure for estimating the growth of the Weibull parameters for thinned loblolly pine plantations that generalized the compatible growth and yield concept developed by Clutter (1963). Also working with loblolly pine plantations but in the West Gulf region, Baldwin and Feduccia (1987) developed prediction and projection equations for the first and 93rd percentiles and the quadratic mean diameter. Separate prediction equations were necessary for stands after an initial thinning and for stands that had received multiple thinnings. The same projection equations were employed for both cases. The Weibull parameter recovery procedure employed utilizes a percentile and moment based iterative procedure for the scale and shape parameters and the direct estimate of the location parameter. Additional Weibull based diameter distribution models for thinned loblolly pine plantations that constrain the parameter recovery procedure to whole stand attributes are reported by Cao et al. (1982) and Matney and Sullivan (1982). A segmented approach to a modified Weibull cumulative distribution function has also been developed to describe diameter distributions in thinned stands (Cao 1982).

In addition to Weibull based diameter distribution models, Hafley and Buford (1985) describe the use of a
truncated bivariate Johnson $S_{bb}$ distribution to model thinning in loblolly pine plantations.

**Effects on Stand Height**

Thinnings or changes in stand density and spacing seem to have little effect on average stand height for loblolly and slash pines in the South. Height growth response to thinning is dependent upon stand density only in stands where overcrowding is severe. Harms and Langdon (1976) reported that differences in height growth became statistically significant at age 12 in dense, naturally seeded loblolly pine stands in the lower coastal plain of South Carolina. At age 12, stands with 8,094 and 16,188 stems per acre averaged 4.3 feet shorter than those on less dense plots. In naturally seeded stands of loblolly pine in southern Arkansas, dominant height at age 21 was 8.2 feet shorter in the unthinned control (30,500 tpa) than those thinned at age 7 to 1,850 stems per acre (Grano 1969). Similar results were reported for dense natural slash pine stands in Georgia (Collins 1967). In this study, 17-year-old dominant and codominant trees grown at 5,762 stems per acre were as much as 10.6 feet shorter than those grown at 366 stems per acre. Stands thinned at age three decreased one foot in height for each 500-tree increase in density over a range from 1,000 to 9,000 stems per acre at age 17. Bennett and Jones (1981) suggested that "Densities beyond 700 trees per acre significantly reduce height growth in young slash pine stands." Other pre-commercial thinning studies in stands less than 5,000 stems per acre have rarely shown increased heights of dominants and codominants (Bower 1965, DeBrunner and Watson 1971, Keister and McDermid 1968, Lohrey 1977).

For pine plantations, thinnings have not increased height growth of the dominant and codominant trees (Bennett 1960b, Keister *et al.* 1968, Dell and Collicott 1968, Wakeley 1969, Parker 1979). This lack of differential height growth in response to thinning has also been reported for lodgepole (Alexander 1965), longleaf (Sparks, Linnartz, and Harris 1980), shortleaf (Williston
The model was fit to both thinned and unthinned stands and explicitly accounts for differences in survival for stands of different productive capacities.

B. Loblolly Pine

Summarizing the results of the Maxwell Study conducted at Urania in central Louisiana, Mann (1952) reported that at age 13, stands thinned lightly from below had less mortality than similar unthinned stands. From age 23 to 40, mortality in unthinned stands was 368 trees per acre compared with 16 trees per acre for those thinned lightly from below. Stands thinned heavily from below, leaving only 100 crop trees per acre, lost only 4 trees per acre. Unlike the results reported for slash pine, Wakeley (1969) reported that stands in southeastern Louisiana thinned at age 19 had less mortality than unthinned stands, but that greater mortality occurred in the more heavily thinned stands. Loblolly pine plantations in Tennessee thinned at 5-year intervals beginning at age 19 exhibited twice the mortality in stands thinned to 70-75 square feet of basal than that found in stands thinned to 120 square feet (Williston 1967). Not all thinning experiments reported increases in mortality with increased thinning intensity. Mortality was found to increase inversely with thinning intensity in a thinning type and intensity study reported by Baldwin et al. (1989). Their results from three loblolly plantations in central Louisiana thinned at age 15, 20 and 21 indicate that mortality increases indirectly with intensity in both row and selectively thinned stands. Average annual mortality (trees per acre) was significantly higher in row thinned stands when compared with stands selectively thinned to the same residual basal area. Stands that were thinned by removing every other and every third row had significantly higher mortality rates than corresponding selectively thinned treatments. Unlike the results reported for slash pine, basal area mortality for loblolly pine stands did not differ between different thinning intensities.
1978) and white pine in the southern Appalachians (Della-Bianca 1981).

**Effects on Crown-Ratio**

Crown-ratio percent is the length of the green crown as a percentage of total tree height. Unlike dominant height, crown-ratio percent has been shown to be affected by thinning intensity (and thus stand density) as well as time of thinning (Chapman 1953, Evans and Gruschow 1954, Bennett 1960b, Dell and Collicott 1968). For loblolly and longleaf pines, Chapman (1953) suggests that normal rates of diameter growth can be maintained by insuring a 40 percent crown-ratio and that mortality begins when this ratio approaches the 10 percent level. Specifically, that diameter growth increases 0.1 inch per year for each 10 percent increase in the ratio beginning at 0.1 for a 20 percent ratio. In addition, stands maintaining this 40 percent ratio and thinned to 50 percent of crown cover at 5-year intervals have exhibited an average diameter growth rate of 3 inches per decade.

In dense stands of natural loblolly pine, height to the base of the green crown was not related to stand density at age 14 though crown size was significantly affected (Harms and Langdon 1976). Bennett (1960b) reported that 7th year crown-ratio percent in slash pine in southeast Georgia was highly correlated with stand density and could be predicted with the following linear relation:

\[
\text{Log(CR)} = 2.40054 - 0.20669 \text{ Log(Density)}
\]

where:

- CR = crown ratio
- Density = trees per acre
- Log = logarithm base 10

A similar relation for slash pine can be derived from the work of Gruschow and Evans (1959):
CR = 103.76475 - 39.339103 \log(D)

where:

D = density as percent of full stocking

Dell and Collicott (1968) also reported that the change in average live crown-ratio of dominants and codominants in slash pine was related to residual density three years following thinning. Average crown-ratio increased in stands thinned to 50 square feet of basal area but decreased in stands with residual densities of 75 square feet and greater.

Several thinning guidelines have been developed utilizing crown-ratio percent as an indicator variable. Mann and Lohrey (1974) suggested that for southern pines, stands below 5,000 trees per acre should be thinned if the average live-crown ratio of dominants and codominants is below 35 percent at the time of first commercial thinning. Bennett (1960a) suggested that since crown-ratio development can only occur during the span of reasonable height growth, thinnings should take place prior to age 35 and that crown-ratios should be maintained above the 30 percent level. Thinning of slash pine at age 35 only increased crown-ratios of dominants and codominants by 3 to 4 percent by age 40 (Bennett and Jones 1981).

**Effects of Thinning on Survival**

By definition, thinning involves the removal of selected trees in order to concentrate growth on the remaining trees. A proportion of the trees removed in thinning would naturally die during the subsequent growth period had they remained as part of the stand. Therefore, after thinning mortality is expectedly less in thinned stands when compared to unthinned stands of similar age and structure. The extent to which mortality is reduced by individual tree removal is logically dependent upon how selective the thinning
operation is against the lesser vigorous individuals. One would expect higher post thinning mortality rates in non-selective row thinning operations than in thinnings that are selective from below. In addition, after thinning mortality should decrease with increasing thinning intensity as the proportion of less vigorous trees removed increases with thinning intensity. The extent to which mortality varies by thinning type, intensity, and stand age has been the subject of many thinning studies over the past 40 years.

A. Slash Pine

In plantations on abandoned fields in southwest Georgia thinned at age 12 or 13, Dell and Collicott (1968) reported that basal area and cubic foot volume mortality was not significantly different for stands thinned to 50, 75 and 100 square feet of residual basal area per acre. However, mortality was significantly higher for stands lightly thinned to 125 square feet. Results reported by Enghardt and Mann (1972) indicated that stands thinned to 85 and 100 square feet of basal area per acre had 4 to 5 times the mortality than stands thinned to 70 square feet. Unthinned check plots in this study averaged 30 times the mortality than that found in stands thinned to 70 square feet but they noted that much of the mortality was due to annosus root rot (*Fomes annosus* (Fr.) Cke.). Similar results, with respect to thinning intensity, were reported for plantations in southeastern Louisiana thinned following the 19th growing season (Wakeley 1969). In a study to quantify the effects of delayed thinning at different intensities, Mann and Enghardt (1972) reported that mortality in thinned stands was lower than that in unthinned stands and generally decreased with increasing thinning intensity. Stands thinned to 70 square feet of residual basal area per acre had lower mortality than stands thinned to either 85 or 100 square feet. In addition, mortality increased as the age at thinning increased from 10 to 16, at 3-year intervals. In a study that investigated both type and intensity of thinning (Baldwin *et al.* 1989), average annual mortality (trees per acre) was significantly higher in unthinned stands and in stands receiving the
row thinning treatments, than in stands selectively thinned to the same residual basal area. Mortality in row thinned stands increased with thinning intensity while it decreased in selectively thinned stands. The lower mortality rates exhibited with selective thinning was also reported by Cremer and Meredith (1976) for radiata pine in Australia, though direct comparison between selective and row thinned treatments were confounded with differences in thinning intensity.

The first survival projection equation for thinned slash pine plantations was reported by Clutter and Jones (1980) for old-field plantations in the Coastal Plain of southern Georgia and northern Florida and the Gulf Coast of Alabama and Mississippi. The model is derived from the differential equation:

$$\frac{1}{N} \frac{\partial N}{\partial A} = \alpha A^r N^q$$

and has the form:

$$N_2 = [N_1^{o_1} + \alpha_2 (A_2^{o_2} - A_1^{o_2})] \frac{1}{\alpha_1}$$

where:

$$N_i = \text{the number of surviving stems per acre at age } i.$$

This model is based on stands that were primarily thinned from below and does not explicitly indicate any functional relationship between the number of surviving trees and site index, thinning intensity, type of thinning, or age at the time of thinning. Working with data from the same study, Bailey et al. (1985) developed a survival function for thinned and unthinned stands that directly incorporated a measure of thinning, age at time of thinning, and site index. The model is based on the differential equation:

$$\frac{1}{N} \frac{\partial N}{\partial A} = \beta_0 + \frac{\beta_1}{A} + \beta_2 S$$
and is of the form:

\[ N_2 = N_1 \left( \frac{A_2}{A_1} \right)^{\beta_1} \exp \left\{ (\beta_0 + \beta_2 S I) (A_2 - A_1) + \beta_3^\top X_t Z \left( \frac{1}{A_2} - \frac{1}{A_1} \right) \right\} \]

where:

\[ Z = \begin{cases} 
1 & \text{if } A_2 < 22.5 \\
0 & \text{if } A_2 \geq 22.5 
\end{cases} \]

\[ X_t = \text{the ratio of the quadratic mean diameter of the trees removed in thinning to the quadratic mean diameter of the whole stand before thinning} \]

\[ A_t = \text{age of stand at last thinning} \]

\[ N_i = \text{number of trees surviving per acre at age } i \]

\[ A_i = \text{stand age at time } i \]

\[ S = \text{site index (base age 25)} \]

Using both thinned and unthinned plantation data from the Flatwoods region of northern Florida and southeastern Georgia, Pienaar et al. (1989) fit the following survival model:

\[ N_2 = N_1 \cdot \exp \left\{ \beta_1 \left( \left( \frac{A_2}{10} \right)^{\beta_2} - \left( \frac{A_1}{10} \right)^{\beta_2} \right) \right\} \]

Parameter estimates for thinned and unthinned stands were not statistically different thus resulting in a single equation. Working with the same data but with additional remeasurements, Pienaar et al. (1990) fit a modified Clutter and Jones (1980) survival projection model of the form:

\[ N_2 = \left\{ N_1^{\beta_1} + \left( \beta_2 + \frac{\beta_3}{S} \right) \left[ \left( \frac{A_2}{10} \right)^{\beta_3} - \left( \frac{A_1}{10} \right)^{\beta_3} \right] \right\}^{\frac{1}{\beta_1}} \]
The published projection equations for survival of thinned loblolly pine plantations do not explicitly include a thinning parameter (Baldwin and Feduccia 1987, Cao et al. 1982, Matney and Sullivan 1982, Lemin and Burkhart 1983). The model developed by Baldwin and Feduccia (1987) for thinned plantations in the West Gulf region is of the form:

\[ N_2 = 100 \left[ \left( \frac{N_1}{100} \right)^{\beta_1} + \left( \frac{\beta_2}{\beta_3} + \frac{\beta_3}{\beta_1} \right)^{\beta_4} \left( \frac{A_2}{10} \right)^{\beta_4} - \left( \frac{A_1}{10} \right)^{\beta_4} \right]^{\frac{1}{\beta_1}} \]

where:
- \( N_i \) = Number of surviving trees at age \( i \)
- \( SI \) = site index
- \( A_i \) = stand age at time \( i \)

Matney and Sullivan (1982), Cao et al. (1982) and Lemin and Burkhart (1983) all fit survival models to thinned old-field plantations. Matney and Sullivan worked with data from plantations in Arkansas, Mississippi, and Tennessee and fit the model:

\[ Y = \alpha_0(A_1 - A_0)^{\alpha_1} \left( \frac{N_0}{B_0} \right)^{\alpha_2} \bar{H}_0^{\alpha_3} \exp \left\{ \alpha_4 B_0 + \alpha_5 \left( \frac{B_0}{A_0} \right) + \frac{\alpha_6}{A_0} \right\} \]

where:
- \( Y \) = the number of trees dying per acre from \( A_0 \) to \( A_1 \)
- \( \bar{H}_0 \) = Average height of dominants and codominant at \( A_0 \)
- \( B_0 \) = initial stand basal area per acre
- \( A_0 \) = initial age
- \( A_1 \) = projection age
- \( N_0 \) = initial trees per acre
- \( N_1 \) = projected trees per acre

The models developed by Cao et al. and Lemin and Burkhart for the Coastal Plain and Piedmont regions of Virginia are a Clutter and
Jones (1980) form, fit to plantation data that were primarily thinned from below. The model form is:

\[ N_2 = \left[ N_1^{\beta_1} + \beta_2 \left( A_2^{\beta_3} - A_1^{\beta_3} \right) \right]^{\frac{1}{\beta_1}} \]

where:
\[ N_i = \text{plantation survival at age } i \]
\[ A_i = \text{plantation age at age } i \]

Effects of Thinning on Basal Area

A. Slash Pine

In all reports reviewed, live basal area per acre was always greater in unthinned stands than in any experimental thinning treatment, however, thinning has been shown to improve basal area growth. Results from dense natural stands in the flatwoods of Georgia and Florida (Gruschow 1949) indicate that light pre-commercial thinning at age 8 to a residual density of 700 trees per acre resulted in greater basal area growth than unthinned treatments. Unthinned plots (3,500 tpa) had approximately 20 percent less basal area growth than the light thinning treatment but exhibited greater basal area growth than the moderate to heavy thinning treatments. In old-field plantations in southwest Georgia thinned at age 12 to 13 to residual basal areas of 50, 75, 100 and 125 square feet per acre, basal area growth increased with residual density to the 100 square foot treatment after which it rapidly decreased (Dell and Collicott 1968). The decrease at the 125 square foot treatment was directly correlated with the increased mortality experienced at this density level. Data reported by Keister et al. (1968) for different thinning treatments established in a 13-year-old slash pine plantation near Bogalusa, Louisiana indicated that the light low and selective thinning treatments doubled basal area growth to age 40 when compared to the unthinned control plots.
These values indicate basal area increments only and do not include that removed in thinnings or lost through mortality. The two thinning treatments were applied at ages 13 and 26 for the selection treatment and at ages 14, 24, and 29 for the light thinning treatment.

In an effort to quantify the effect of stand age at time of thinning, Mann and Enghardt (1972) reported on plantations in southwest Louisiana thinned to residual basal areas of 70, 85 and 100 square feet at age 10, 13 and 16. Deferring thinnings to age 16 decreased live basal area while total basal area production decreased with increasing residual density. Little difference was found between plots thinned to 70 and 85 square feet of basal area.

A prediction equation for periodic basal area growth for cutover slash pine plantations in west central Louisiana was developed by Feduccia (1977). Plantations were thinned at five year intervals starting at age 14 and 16. The equation is a function of stand age, site index and basal area. Basal area growth increased with site index and residual density and decreased with age. Annual basal area growth ranged from 0.09 to 0.35 square feet per 10 square foot increase in residual density. For the two growth periods tested (15-20 years and 20-25 years) basal area growth declined approximately 1.4 ft²/ac./yr. during the second growth period.

Clutter and Jones (1980) provided the first regional study of thinned slash pine plantations on old-field sites ranging from the coastal plain of south Georgia and northern Florida to the Gulf Coast of Alabama and Mississippi. They developed a basal area projection equation for thinned stands as a function of age and initial basal area:

\[
\ln(B_2) = \left( \frac{A_1}{A_2} \right)^{\beta_1} \ln(B_1) + \beta_2 \left[ 1 - \left( \frac{A_1}{A_2} \right)^{\beta_1} \right]
\]

This model form for thinned stands assumes that thinned and unthinned stands grow at the same rate if they start at the same age with the same initial basal area. This model form does have the desirable properties:
1) \( \text{limit } \ln(B2) = \ln(B1) \) \\
\( A1 \rightarrow A2 \)

2) is path invariant

3) is asymptotic as \( A2 \rightarrow \infty \)

Pienaar (1979) introduced the idea that basal area growth in thinned stands was greater than for unthinned stands of the same age, site, and planting density. He developed an index of suppression of the form:

\[
IS = \frac{B_u - B_t}{B_u}
\]

where:

\( IS \) = index of suppression

\( B_t \) = basal area per acre of the thinned stand immediately following thinning

\( B_u \) = basal area per acre in the unthinned stand of the same age, site and planting density

Basal area growth of thinned stands was obtained by adjusting the projected growth of the similar unthinned stand by the equation:

\[
b = (1-IS_{t2}) B_{t2} - (1-IS_{t1}) B_{t1}
\]

where:

\( b \) = basal area growth after thinning from age \( t_1 \) to \( t_2 \)

\( B_{t1} \) = basal area per acre for an unthinned stand at time \( t_1 \)

\( IS_{t1} \) = index of suppression at time \( t_1 \)

This same concept was later applied to 45-year-old thinned and unthinned slash pine plantations in South Africa (Pienaar and Shiver 1984) where observed basal area growth in the thinned plots exceeded the expected growth of the unthinned plots in most cases. The authors suggest that basal area growth in thinned stands will asymptotically approach that of unthinned stands of the same age,
site index, and stems per acre and that yield models that do not allow for a growth response due to thinning may significantly underestimate the yield of thinned stands.

In an attempt to provide a compatible basal area growth and yield model for thinned and unthinned stands, Bailey and Ware (1983) developed a model that explicitly includes a function of the type of thinning as well as the time since last thinning. The model is of the form:

\[ B_2 = B_1^{\left(\frac{A_1}{A_2}\right)} \exp\left\{ \beta_1 \left(1 - \frac{A_1}{A_2}\right) + \beta_2 \frac{X_t}{A_1} \left(\frac{1}{A_2} - \frac{1}{A_1}\right) + \beta_3 S \left(1 - \frac{A_1}{A_2}\right) \right\} \]

where:
- \( B_i \) = basal area per acre at age \( i \)
- \( S \) = site index (base age 25)
- \( A_t \) = age at most recent thinning (\( A_t \leq A_1 \))
- \( X_t = 1 - R_t, \quad \text{if } R_t \neq 0 \)
  \[ = 0, \quad \text{if } R_t = 0 \]
- \( R_t \) = ratio of the quadratic mean diameter of the trees removed in thinning to the quadratic mean diameter of the stand before thinning

The proposed model has the desirable properties:

a) \( \lim_{A_1 \rightarrow A_2} B_2 = B_1 \)

b) \( \lim_{A_2 \rightarrow \infty} B_2 = \exp(\beta_1 + \beta_3 S) \)

c) projection is path invariant

d) If \( \beta_2 < 0 \) then \( B_2 \) is a monotonic increasing function of \( X \)

e) If \( X=0 \) the model reduces to the commonly used functional form for basal area growth suggested by Clutter (1963)
Property (e) implies that basal area growth for diameter-indifferent thinnings, such as row thinnings, would be no different than unthinned stands of the same initial basal area since \( X=0 \) in this type of thinning. The model also implies that thinning from above (\( X<0 \)) will grow less and that thinning from below (\( X>0 \)) will grow more than unthinned stands of the same initial basal area. Empirical tests on slash, loblolly, and western larch substantiated the effectiveness of this model in projecting basal area growth in thinned plantations. Pienaar, Shiver, and Grider (1985) also developed a thinning response model that included an explicit function of thinning intensity based on a basic basal area growth model suggested by Schumacher (1939) and generalized by Clutter and Jones (1980):

\[
B_2 = B_1 \left( \frac{A_1}{A_2} \right)^{\beta_2 + \beta_1 X} \exp \left\{ \beta_2 \left[ 1 - \left( \frac{A_1}{A_2} \right)^{\beta_2 + \beta_1 X} \right] \right\}
\]

where:

\( B_i \) = basal area per acre at age \( A_i \) years from planting

\( X \) = \( \frac{TPA_t}{TPA_a} \) where \( TPA_t \) and \( TPA_a \) are the trees per acre removed in thinning and remaining after thinning, respectively.

Initial tests of the slash pine plantations in South Africa indicated that basal area projections could be significantly improved by distinguishing between thinned and unthinned plantations of the same basal area and age. Incorporation of the measure of thinning intensity significantly improved (\( \alpha = 0.10 \)) basal area projection over the Clutter and Jones (1980) model form. The compatible model form has the desirable properties:

a) both yield model and growth projection model reduce to the general Clutter and Jones (1980) form when no thinning is applied (\( X=0 \))
b) both thinned and unthinned plantations are assumed to have the same asymptotic basal area on any given site. The rate at which it is approached depends on the age at which the thinning occurs and on the thinning intensity.

Utilizing the same data, an additional reduction in the residual sum of squares was obtained by modifying the expected growth of unthinned plantations. Iterative solutions for one year planting survival, basal area growth for unthinned plantations, and solution of the index of suppression at the projection age are required to predict basal area for thinned stands. Beginning with a general Schumacher-type variable density yield equation form, Pienaar and Shiver (1986) developed stand-level basal area yield and projection equations for thinned and unthinned slash pine plantations in South Africa that explicitly include a modifier term to account for thinning intensity and the plantation age at the last thinning:

\[
\ln(B) = \beta_0 + \beta_1 \left( \frac{1}{A} \right) + \beta_2 \ln(N) + \beta_3 \ln(H) + \beta_4 \frac{\ln(N)}{A} + \\
\beta_5 \frac{\ln(H)}{A} + \beta_6 \frac{N_t A_t}{N_a A}
\]

where:

- \( A_i \) = plantation age at age \( i \)
- \( B_i \) = basal area per acre at age \( i \)
- \( N_i \) = trees per acre at age \( i \)
- \( H_i \) = average dominant height at age \( i \)
- \( N_t \) = number of trees per acre removed at thinning
- \( N_a \) = number of trees per acre remaining in the stand after thinning
- \( A_t \) = plantation age at last thinning

The modifier term \((N_t A_t/N_a A)\) provides logical results for predicting the effects of different thinning intensities when \( A \), \( A_t \), and \( N_a \) are the same and for earlier thinnings holding \( A \) and intensity \((N_t/N_a)\) constant. The projection form of this yield equation is of the form:
\[ \ln(B2) = \ln(B1) + \beta_1 \left( \frac{1}{A2} - \frac{1}{A1} \right) + \beta_2 (A2 - A1) + \beta_3 \left( 1 - \frac{A1}{A2} \right) + \beta_4 \left[ \left( \frac{1}{A2} \right)^2 - \frac{1}{A1 A2} \right] + \beta_5 \ln(N1) \left( \frac{1}{A2} - \frac{1}{A1} \right) + \beta_6 \ln(H1) \left( \frac{1}{A2} - \frac{1}{A1} \right) + \beta_7 \left( \frac{Nt At}{Na A2} - \frac{Nt At}{Na A1} \right) \]

In this particular data set \( \beta_3 \) and \( \beta_6 \) were not significantly different from zero (\( \alpha = 0.05 \)). No attempt was made to account for cross equation correlation between error terms for the dominant height or survival functions.

Similar whole stand models were also fit to thinned slash pine plantation data in the Atlantic Coast Flatwoods (Pienaar 1989, 1990). Both are based on a similar prediction equation that includes a slightly modified thinning component than that described earlier by Pienaar and Shiver (1986):

\[ \ln(B) = \beta_0 + \beta_1 \left( \frac{1}{A} \right) + \beta_2 \ln(H) + \beta_3 \ln(N) + \beta_4 \left( \frac{\ln(H)}{A} \right) + \beta_5 \left( \frac{\ln(N)}{A} \right) + \beta_6 \left( \frac{Nt At}{Nb A} \right) \]

The first projection equation (Pienaar et al. 1989) is of the form

\[ \ln(B2) = \ln(B1) + \beta_1 \left( \frac{1}{A2} - \frac{1}{A1} \right) + \beta_2 (\ln(H2) - \ln(H1)) + \beta_3 (\ln(N2) - \ln(N1)) + \beta_4 \left( \frac{\ln(H2)}{A2} - \frac{\ln(H1)}{A1} \right) + \beta_5 \left( \frac{\ln(N2)}{A2} - \frac{\ln(N1)}{A1} \right) + \beta_6 \left( \frac{Nt At}{Nb A2} - \frac{Nt At}{Nb A1} \right) \]

which is derived through the elimination of the intercept (\( \beta_0 \)) parameter while the second projection equation (Pienaar et al. 1990) is of the form:
\[ \ln(B2) = \frac{A1}{A2} \ln(B1) + \beta_0 \left(1 - \frac{A1}{A2}\right) + \beta_2 \left(\ln(H2) - \frac{A1}{A2} \ln(H1)\right) + \]
\[\beta_3 \left(\ln(N2) - \frac{A1}{A2} \ln(N1)\right) + \beta_4 \left(\frac{\ln(H2) - \ln(H1)}{A2}\right) + \]
\[\beta_5 \left(\frac{\ln(N2) - \ln(N1)}{A2}\right)\]

and is derived through the elimination of the coefficient of the inverse of age parameter \(\beta_1\). In this derivation, the thinning term cancels in the projection equation.

### B. Loblolly Pine

Results for basal area growth for loblolly pine are similar to those mentioned for slash pine, though model development is not nearly as extensive. In very dense naturally seeded loblolly stands in the lower coastal plain of South Carolina, basal area increased directly with density (tpa) in stands that were pre-commercially thinned at age 3 (Harms and Langdon 1976). This increase was most rapid at densities up to the 4,000 trees per acre treatment through age 12 but continued to increase through the 16,000 trees per acre treatment at age 14. Mann (1952) reported on the Maxwell thinning study conducted in central Louisiana on a natural old-field site. The data included basal area before and after thinnings at 5 and 10-year intervals. The unthinned and the lightly thinned treatments were both established at age 8 and had similar initial basal areas. Total basal area growth, excluding that cut in thinnings and that lost to mortality, was 60% higher in the lightly thinned treatment than in the unthinned check plot. The unthinned plot exhibited negative basal area growth between age 33 and 44 because of mortality. On old-field plantations thinned at 5-year intervals beginning at age 19, basal area growth was greater than that of the unthinned plots for all thinning treatments tested with little variation between thinning treatments. Average annual basal area increment for all thinned plots was 4.01 ft²/ac./yr. between age 19 and 24 and 3.49 ft²/ac./yr. from age 24 to 29. The unthinned
check plots only increased 2.76 and 0.50 ft²/ac./yr. for these same two periods. Seventeen-year results from a spacing study conducted on cutover sites in southwest Louisiana (Mann and Dell 1971) showed that basal area per acre increased directly with initial planting density and with site index. For 70 and 75 foot sites, basal area plateaued at 1,100 trees per acre but continued to increase on better sites with planting densities up to 1,200 trees per acre. Live basal area on site 105 plots was 50% higher than those on site 70 plots. The authors presented a basal area prediction equation for 17-year-old stands as a function of site index and initial planting density.

The first whole stand basal area projection equations did not include an explicit measure of thinning type or intensity. The equations were fit to repeatedly thinned stands (Cao et al. 1982, Burkhart and Sprinz 1984) and both thinned and unthinned stands (Matney and Sullivan 1982). Matney and Sullivan reported on repeatedly thinned old-field plantations in Arkansas, Mississippi, and Tennessee. Their procedure projected mean basal area per tree that was subsequently multiplied by the projected number of trees per acre to calculate projected basal area. Mean annual change of average basal area per tree was projected with the following equation:

\[ W = \alpha_0 B_0^{\alpha_1} H^{\alpha_2} A0^{\alpha_3} \exp\left( \alpha_4 B_0^{\alpha_5} + \alpha_6 B_0^{\alpha_7} \right) \]

where:

\( W = (\bar{B}_1 - \bar{B}_0)/(A1 - A0) \) is the mean annual change of mean basal area per tree in square feet.

\( \bar{B}_0 \) = average basal area per tree in square feet at age \( A0 \)

\( B_0 \) = initial basal area per acre

\( A0 \) = initial age
\[ \overline{B}_1 = \overline{B}_0 + (A1 - A0)W \] is the projected average basal area per tree in square feet at age A1

\[ \overline{H} \] = average height of dominants and codominants

The current observed basal area per tree was used to project basal area for thinned stands, thus assuming that both thinned and unthinned stands starting with the same initial basal area would experience the same rate of basal area growth. Cao et al. (1982) developed a whole stand basal area model for repeatedly thinned old-field plantations in the Virginia Piedmont and Coastal Plain. Plantations were operationally thinned up to three times, primarily from below. The basal area projection model is of the form:

\[
\ln(B2) = \beta_0 + \beta_1 S - \left( \frac{A1}{A2} \right) \left[ \beta_0 + \beta_1 S - \ln(B1) \right]
\]

where:

\[ S \] = site index in feet (base age 25)

\[ A_i \] = plantation age at age \( i \)

\[ B_i \] = basal area in square feet at age \( i \)

Although the model was fit to thinned plantation data, there is no explicit measure of either thinning type or intensity. The model is path invariant, does equate to \( \ln(B1) \) as \( A2 \rightarrow A1 \), and has a site specific upper asymptote. Working with data from the same region, Burkhart and Sprinz (1984) developed compatible basal area and volume growth and yield equations. These equations were simultaneously fit with a combined loss function that gave equal weights to basal area and volume residuals. The basal area projection equation for repeatedly thinned plantations is of the form:

\[
\ln(B2) = \left( \frac{A1}{A2} \right) \ln(B1) + \alpha_1 \left( 1 - \frac{A1}{A2} \right) + \alpha_2 S \left( 1 - \frac{A1}{A2} \right)
\]
Working in stands where past thinning history was unknown, McTague and Bailey (1987) developed compatible basal area and diameter distribution models for thinned plantations in Santa Catarina, Brazil. This method developed through the premise that in stands where past thinning history is unknown, response to thinning could be captured through the change in diameter distribution percentiles over time. The basal area projection model incorporates an implicit measure of thinning as defined by the change in the 10\textsuperscript{th} and 63\textsuperscript{rd} percentiles over time:

\[
\begin{align*}
\ln(B_2) &= \beta_0 \left( \frac{1}{A_2} - \frac{1}{A_1} \right) + \beta_1 \ln\left( \frac{N_2}{N_1} \right) + \beta_2 \ln\left( \frac{D_{63_2}}{D_{63_1}} \right) + \beta_3 \ln\left( \frac{D_{10_2}}{D_{10_1}} \right) + \\
&\beta_4 \left( \frac{1}{D_{63_2} - D_{10_2}} - \frac{1}{D_{63_1} - D_{10_1}} \right) + \ln(B_1)
\end{align*}
\]

The model exhibits the desirable properties of path invariance, equates to \( \ln(B_1) \) as \( A_2 \to A_1 \), but is unbounded as \( A_2 \to \infty \). However, the authors report that the basal area values are reasonable within the range of observed plot values (9 - 253 ft\(^2\)/ac.).

Model forms that explicitly incorporate a measure of thinning type or intensity are few. As discussed previously, Bailey and Ware (1983) fit their basal area projection equation to thinned natural stands of loblolly pine utilizing the ratio of the quadratic mean diameter of trees removed in thinning to the quadratic mean diameter of the whole stand before thinning. Souter (1986) developed compatible survival and basal area functions for naturally-regenerated loblolly pine in the Georgia Piedmont. The basal area projection model is of the form:

\[
B_2 = \left( \frac{N_2}{N_1} \right)^{A_1/A_2} B_1 \left( \frac{A_1}{A_2} \right) \exp \left\{ (\alpha_1 + \alpha_3 S) \left( 1 - \frac{A_1}{A_2} \right) + \right. \\
\left. \alpha_2 \left( \frac{Dr}{Db \times SDib} \right) \left( \frac{1}{A_2} - \frac{1}{A_1} \right) \right\}
\]
where:

\[ \begin{align*}
N_i &= \text{per acre survival at age } i \\
A_i &= \text{stand age at age } i \\
B_i &= \text{stand basal area per acre at age } i \\
S &= \text{site index} \\
D_r &= \text{quadratic mean diameter removed in thinning} \\
D_b &= \text{quadratic mean diameter before thinning} \\
SDI_b &= \text{Reineke's stand density index before thinning} \\
A_t &= \text{stand age at thinning}
\end{align*} \]

This equation form includes the predicted value for survival at age 2 as well as an explicit measure of thinning which is a modification of the Xt variable presented by Bailey and Ware (1983). The survival and basal area projection models were fit as a system of equations using a simultaneous least-squares estimation procedure.

**Effects of Thinning on Stand Volume**

### 7.1 Total Volume

The effect of thinning upon total standing cubic foot volume is most dramatic with stands of high initial density, a situation which can develop with natural and direct seeded stands. In dense, naturally seeded stands in the lower coastal plain of South Carolina, total cubic foot volume (\(\text{ft}^3\)) at age 14 increased with density to approximately 4,000 trees per acre (Harms and Langdon 1976) and then stabilized for treatments with densities through 16,000 trees per acre. The authors suggest that "The volume plateaus thus formed were logically the result of the reduction in average tree height that occurred as density increased." In direct seeded stands in the West Gulf Coastal Plain of central Louisiana, total cubic foot volume (\(\text{ft}^3\)) at age 16 increased directly with stand density for stands receiving a pre-commercial thinning at age 3 (Lohrey 1977). At age 16, the greatest total volume was found on the unthinned check plots that had an initial density of 5,033 trees per acre and least on those
thinned to 750 trees per acre. When considering only those trees greater than 5.5 inches dbh, total volume decreased directly with residual density following thinning.

On cutover stands that are more indicative of operationally managed plantations, Feduccia and Mann (1976) reported that in stands thinned from below to five spacings at age 17, gross annual periodic volume growth (ib) to age 22 increased directly with residual basal area and site index. Gross periodic annual volume growth increased between 9 and 24 cubic feet per acre for each 10 square foot increase in basal area and between 10 and 17 cubic feet per acre for each 10-foot increase in site index. Differences in volume growth were greatest in plots with lower site indices and at lower densities. Regression equations were presented that predicted annual periodic growth as a function of site index and residual basal area. Estimated volume growth for unthinned plots was larger than for any thinning treatment tested. Spacing at the time of planting was not found to be a significant indicator of post thinning volume growth. Periodic volume increment ranged from 150 cu.ft./ac./yr. on heavily thinned plots on site 80 to over 300 cu.ft./ac./yr. on unthinned plots on 110-foot sites. A long term analysis of old-field loblolly pine was described by Mann (1952) in his review of the Maxwell study at Urania, Louisiana. To age 33, all repeatedly thinned plots had lower periodic annual cordwood growth than the unthinned control plots. During this period, growth increased directly with increasing residual basal area. From age 33 to 44, mortality greatly increased on the unthinned plots, reducing their periodic annual cordwood growth below that of all thinning treatments. Mann suggests that if maximum cubic foot growth is desired on a long rotation, thinning should be very light and should concentrate on the defective and suppressed trees. Conversely, if shorter rotations are desired, maximum volume will be obtained on unthinned stands or stands thinned very lightly. The study indicates that maximum volume would occur on unthinned stands (assuming that stands are not excessively dense) until that time when natural mortality of the suppressed trees increases in these stands. According the data presented, this would occur after age 33.
7.2 Merchantable Volume

A. Loblolly Pine

As was the case with total cubic foot volume, only overly dense stands exhibited an increase in merchantable volume growth to thinning (Grano 1969). Reports of merchantable cubic foot volume growth in natural stands of loblolly pine in Georgia, Virginia, and South Carolina indicated that periodic annual growth five years following thinning was related to residual stand density and site index (Wenger et al. 1958). The relation of growth to density varied with site quality, with denser stands growing faster on good sites but slower on poorer ones. Five-year periodic annual growth equations for thinned and unthinned stands were presented as a linear function of site index, density (percent stocking), age and the interaction between site and density. This same interaction of site and residual density was also reported by McClay (1955) with loblolly pine in the piedmont and coastal plain regions of Virginia and the Carolinas. Wenger et al. (1958) suggested that since the slope of the periodic cubic foot growth curve was negative for the poorer sites over the range of the densities tested, the true relation must be curvilinear. This concept was supported by Nelson et al. (1961) who reported on the second five-year growth results for the same study. Their conclusions confirmed many of Wenger's original results and the authors provide 5-year net annual merchantable growth prediction equations for thinned and unthinned stands with the inclusion of age and residual basal area in the thinned stand equations. Periodic annual cubic foot growth varied inversely with age and increased directly with density (BA) and site index. Culmination of growth occurred at higher densities on better sites. The first partial derivative of the growth prediction equation, with respect to basal area, exemplifies this response:
<table>
<thead>
<tr>
<th>SI</th>
<th>Maximum BA</th>
<th>% increase</th>
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</tr>
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<td>11.1</td>
</tr>
<tr>
<td>110</td>
<td>164.1</td>
<td>10.0</td>
</tr>
</tbody>
</table>

The first merchantable volume prediction equations for thinned stands on cutover sites were provided by Mann and Dell (1971) for 17-year-old loblolly plantations in southwest Louisiana. Inside and outside bark volume prediction equations for two diameter thresholds were presented as functions of site index and the number of planted trees per acre. Maximum volumes were obtained at closer initial spacings on better sites than on poorer ones and yields at age 17 were approximately 2.5 times greater for site index 100 than for site index 70 sites. These initial spacing trials were subsequently thinned to residual basal areas between 60 and 120 square feet per acre and the five year results presented by Feduccia and Mann (1976). Gross periodic annual volume growth, inside bark, five years following thinning at age 17 was predicted as a function of site index and residual basal area. Residual basal area was more important in predicting future volume growth than numbers of trees, which was used in earlier work by Mann and Dell (1971). Each 10 square foot increase in residual basal area increased volume growth by 9 to 24 cubic feet annually. Each 10-foot increase in site index increased volume by 10 to 17 cubic feet per acre. Thinning to a basal area of 120 square feet per acre increased volume growth 1.6 times over that obtained when thinning to a residual density of 60 square feet. No thinned plot exhibited greater 5-year volume growth than the unthinned controls. The authors suggested that first thinnings should begin when basal area attains or exceeds 100 square feet.

Development of forest volume growth projection models for thinned loblolly pine plantations have been based primarily on compatible projection equations of the form described by Clutter
(1963) and later extended by Sullivan and Clutter (1972). Matney and Sullivan (1982) developed the following total cubic foot volume equation for old-field loblolly pine in Mississippi, Louisiana, and Tennessee:

\[ V = N \left[ f' + f_0 Q^f c_0^2 \exp \left( f_3 \left( \frac{c_1}{Q} \right) + f_4 \left( \frac{c_0}{A} \right) \right) \right] \]

where:
\[ c_0 \text{ and } c_1 \] = the intercept and slope coefficients of the height-dbh curve
\[ V \] = total per acre cubic foot volume (ib)
\[ A \] = stand age
\[ N \] = number of trees per acre
\[ Q \] = quadratic mean diameter
\[ f' \] = the intercept coefficient from the assumed volume equation

This model was fit to thinned data but does not explicitly include a measure of thinning type or intensity and assumes that thinned and unthinned stands of the same age, trees per acre and basal area exhibit the same volume growth.

Burkhart and Sprinz (1984) developed compatible cubic foot volume and basal area projection models for repeatedly thinned old-field loblolly pine in the piedmont and coastal plain of Virginia. Their volume and basal area projection equations were fitted simultaneously with a loss function that allocated equal weights to both volume and basal area projection. The cubic foot volume projection equation is of the form:

\[ \ln(Y_2) = \beta_0 + \beta_1 S + \frac{\beta_2}{A_2} + \frac{\beta_3}{A_2} \ln(B1) + \beta_4 \left( 1 - \frac{A1}{A2} \right) + \beta_5 \left( 1 - \frac{A1}{A2} \right) S \]

where:
\[ Y_2 \] = per acre cubic foot volume (ob) to a 4-inch dob top for all trees 5.0 inches dbh and larger
\[ S = \text{site index (base age 25) in feet} \]
\[ A_i = \text{stand age at time } i \]
\[ B_i = \text{total basal area in square feet per acre at time } i \]

As with the Matney and Sullivan model (1982), this model does not explicitly include a measure of thinning type or intensity and also assumes that similar thinned and unthinned stands have the same rate of volume growth.

A volume growth model that was fit with both a mortality function and a basal area function that directly incorporated a measure of thinning was developed by Souter (1986) for natural stands of loblolly pine in the Georgia piedmont:

\[ V_2 = \exp \left( \beta_1 + \beta_2 S + \frac{\beta_3}{A_2} + \beta_4 \ln(B_2) + \beta_5 \ln(N_2) + \beta_6 \left( \frac{B_2}{N_2} \right) + \beta_7 \left( \frac{N_r}{N_b} \right) \right) \]

where:
\[ V_2 = \text{merchantable cubic foot volume at time 2} \]
\[ S = \text{site index} \]
\[ A_2 = \text{stand age at time 2} \]
\[ B_2 = \text{basal area at time 2} \]
\[ N_2 = \text{stems per acre at time 2} \]
\[ N_r = \text{stems removed in last thinning} \]
\[ N_b = \text{stems per acre before last thinning} \]

This model directly incorporates the ratio of the number of trees removed during thinning to the number present before thinning as a measure of thinning intensity and an estimate of basal area based upon a model form that incorporated an explicit function of thinning intensity and age at thinning.

**B. Slash Pine**

The earliest reports on the effects of thinning on merchantable volume in slash pine in the Southeast were from very
dense naturally seeded stands. Gruschow's (1949) experiments with pre-commercial thinnings in 8-year-old stands on the Olustee Experimental Forest at Olustee, Florida indicated that cordwood volume 10 years following thinning was 11% higher in unthinned plots (27.2 cdfs/ac.) than in those plots receiving the light thinning treatment (24.5 cdfs/ac.). All plots were thinned again at age 18 and by age 22 the light thinning treatment produced the largest total merchantable volume (33.8 cdfs/ac.) and had the largest periodic annual growth rate (2.3 cdfs/ac.). Working at the same location and in stands with the same initial densities (3,500 tpa), Cooper (1955) reported that stands pre-commercially thinned at age 10 had greater merchantable cubic foot volume (1,625 ft³/ac.) at age 20 than the unthinned control plots (640 ft³/ac.). Similar results to Cooper's were also reported by McMinn (1965) for stands in north Florida and south Georgia and by Collins (1967) in slightly denser stands in Georgia. Collins reported that merchantable cubic foot volume increased as density decreased to 426 trees per acre after which volume decreased directly with density. Reviewing many of the early experiments, Gruschow and Evans (1959) developed a prediction equation for periodic annual volume growth in these dense stands as a function of percent stocking, age, site index and the interaction between site and density. Maximum growth per acre was attainable at less than full stocking, especially on poorer sites and the same volume growth could be produced over a wide range of stocking levels. McMinn (1965) reported that mean annual cubic foot growth for all thinning treatments culminated between ages 22 to 27. Insight to the effects of density on merchantable volume production for planted stands was provided by a spacing study on the Georgia Walton Experimental Forest (Harms and Collins 1965). Results at the end of 12 growing seasons showed little variation in merchantable volume per acre for spacings between 400 and 900 trees per acre. Volumes were lower for the extreme spacings having 194 and 1,210 trees per acre. In a long term thinning experiment established in 13-year-old plantations in southeast Louisiana (Keister et al. 1968), total merchantable cubic foot volume production to age 29 (including standing and cut volumes) varied
little for all thinning treatments. However, total volume production to age 40 was greatest in the lightly thinned plots (both low and crown thinnings) and least in the unthinned controls. In an attempt to identify an applicable measure of thinning intensity, Dell and Collicott (1968) reported on 3-year results from an old-field plantation in southwest Georgia thinned at age 12 and 13 to 50, 75, 100 and 125 square feet of basal area per acre. Net merchantable cubic foot volume growth increased directly with residual basal area from 50 to 100 square feet but leveled off at the 125 square foot treatment. The authors suggest that thinning to 100 square feet was ideal for the conditions tested. Enghardt and Mann (1972) also reported on the superiority of thinning to the 100 square foot level in their summary of the 10-year results from thinning planted stands at age 17 in the flatwoods region of the West Gulf Coastal Plain. Plots were thinned to 70, 85 and 100 square feet of basal area per acre. Volume growth during the first 5 years following thinning was directly related to basal area at the time of thinning. Ten-year annual growth increased directly with basal area. Periodic annual cubic foot volume growth (lb) was statistically larger for plots thinned to 100 square feet than those thinned to 85 or 70 square feet, but not different than the unthinned check plots. For these treatments, there was an average increase of 25 cubic feet for each additional 15 square feet of basal area per acre. Twenty-year results from similar sites in this same region (Feduccia 1979) exhibited the same response with respect to residual basal area. Net periodic annual volume growth for the 20-year period was best on plots repeatedly thinned to 100 ft² every 5 years and for plots thinned initially to 95 ft² and then to 115 ft² at 5-year intervals, while it was least for the check plots and for the heavily thinned treatments. For stands thinned to 70, 85, and 100 square feet of basal area per acre there was a 19 cubic foot increase in merchantable volume per acre with each 15 square foot increase in basal area. Heavy mortality occurred in the check plots between ages 27 to 37, resulting in the 100 square foot treatment producing 31% more volume while the 70 square foot treatment produced only 8% more volume than the check plots. In addition, net mean annual
cubic foot volume growth was greatest in the 100 square foot treatment (186 ft³/ac.) and least for the unthinned plots (138 ft³/ac.). Mean annual cubic foot volume growth had peaked in the unthinned plots between age 27 and 32 but had not peaked in any of the thinning treatments. Total net yields ranged from 5,106 ft³/ac. in the check plots to 6,882 ft³/ac. in the 100 square foot treatment.

Ten-year results from thinned slash pine plantations on medium to poor cutover sites in the West Gulf region were reported by Feduccia (1977). Plots were thinned at age 14 and 16 to residual basal areas between 40 and 130 square feet per acre. Maximum volumes were obtained for the highest residual basal area treatments for all site indices tested. On the average, a 10 square foot increase in residual basal area increased periodic cubic foot volume growth from 7 to 23 cubic feet per acre. The largest increase was associated with changes at the lower density levels. An incremental increase of site class by 10 feet resulted in a 41 to 50 cubic foot increase in annual periodic volume growth. Thinning reduced total yield below that of the unthinned check plots. Periodic annual volume growth projection equations were developed as a function of site index, age, basal area, and the interaction between site and density.

Little information is available on the effect of thinning age on volume production. On cutover sites in central Louisiana, stands were thinned to 70, 85 and 100 square feet of basal area per acre at ages 10, 13 and 16 (Mann and Enghardt 1972). Total yield and mean annual growth in cubic feet per acre (ob) for trees greater than 3.6 inches dbh decreased with intensity of thinning and increased with age of thinning with the exception of the treatment thinned to 100 square feet at age 10 which exceeded all treatments in both total yield and mean annual growth. Thinning to 100 square feet of basal area appears superior to other thinning intensities over the 9-year period, though substantial differences in initial treatment volumes overshadows these comparisons. In a regional study of thinned old-field plantations from south Georgia and north Florida to the Gulf Coast of Alabama and Mississippi (Clutter and Jones 1980), thinnings reduced cubic foot volume production in all cases.
considered. The percentage decrease in cubic foot volume production increased directly with earlier thinning ages, increased directly with thinning intensity, and increased directly with increasing stand density at lower site classes while increasing inversely with stand density for higher site classes.

Total stem volume (lb) prediction and compatible projection equations were developed for slash pine plantations in the Atlantic Coast Flatwoods (Pienaar et al. 1990). The projection equation is of the form:

\[
\ln(V_2) = \ln(V_1) + \beta_1 \left( \frac{\ln(H_2)}{A_2} - \frac{\ln(H_1)}{A_1} \right) + \beta_2 (\ln(N_2) - \ln(N_1)) + \beta_3 (\ln(B_2) - \ln(B_1))
\]

where:

- \( V_i \) = total stem cubic foot volume (lb) at age \( i \)
- \( H_i \) = average dominant/codominant height at age \( i \)
- \( N_i \) = surviving trees per acre at age \( i \)
- \( B_i \) = basal area per acre at age \( i \)

This equation form was simultaneously fit with dominant and codominant height, survival, and basal area projection equations utilizing both thinned and unthinned plantation data. The same data was also used to fit a per-acre merchantable volume prediction equation as initially developed by Amateis et al. (1986). This equation form can be used to apportion total stand volume into volumes by desired product classes.

### 7.3 Board Foot Volume

One of the main objectives of thinning is to concentrate stand growth on a fewer number of stems with the hopeful outcome of producing larger size products in a shorter period of time. The amount of board foot volume and the age at which it is produced is a measure or indicator of the effectiveness of thinning to produce these larger products. The premise that thinning accelerates board
foot production is supported, at least in part, by all the studies reviewed with the exception of the Maxwell thinning study in central Louisiana (Mann 1952) and in a loblolly pine plantation on an excellent site in southeast Georgia (Xydias et al. 1982). In the Maxwell study, total board foot volume production for old-field loblolly pine stands was reduced by all thinning treatments. By age 44, light thinnings from below and the crop tree thinning treatment had reduced total board foot volume per acre by 5.47% and 9.35%, respectively. However, average annual sawtimber increment between age 39 and 44 was greatest in the early light thinning treatment (634 bd.ft.) and least in the unthinned check plots (346 bd.ft.). Heavy ingrowth was still occurring in all stands. In the loblolly pine plantation thinned at age 11 to 100, 200 and 300 trees per acre (Xydias et al. 1982), site quality exceeded 80 feet (base age 25) and prethinning volume averaged 3,100 cubic feet per acre. Ten years after thinning, the unthinned controls contained the greatest total cubic foot volume for all trees and the largest board foot volume (International) for trees at least 8 inches dbh. However, stands thinned to 100 and 200 trees per acre contained more board foot volume in trees at least 13 inches dbh.

In dense natural slash pine stands in northern Florida and southern Georgia pre-commercially thinned at age 7 to 700, 400, 200 trees per acre (McMinn 1965), sawtimber volume increased with thinning intensity through age 35. Stands initially thinned to 200 and 400 trees per acre had more than 2.5 times the volume of the unthinned plots at age 35. Five-year periodic annual board foot volume growth equations for thinned and unthinned natural loblolly pine stands in Georgia, Virginia, and South Carolina were published by Wenger et al. (1958). These linear prediction equations are a function of site index, age, density (percent of theoretical full stocking) and the interaction of site and density. In young stands growth increased with increasing density on good sites but deceased on poorer sites. In older stands growth increased directly with density on all sites, though growth on poorer sites was not as good as that for higher quality sites. The authors suggest that the density for maximum board foot volume growth is higher in older
than in younger stands. Reporting on later remeasurements from the same study, Nelson et al. (1963) developed similar periodic board foot volume prediction equations based on site, age and density in terms of residual basal area per acre. The results support the findings of the earlier report (Wenger et al. 1958) and reemphasize the significance of the site*density interaction in the volume prediction model. Cubic foot growth tended to maximize at higher stand densities than board foot growth, the difference being more pronounced on poorer sites. The authors also report that board foot growth decreased over age 30 for all sites and densities tested.

Langdon and Bennett (1976) suggest that yields of natural stands of slash pine can equal those of plantations if these stands are thinned at an early age.

Thinning results for old-field plantations have been reported through a regional study of slash pine by Clutter and Jones (1980) and by Burton (1982) and Parker (1979) for loblolly plantations. The regional study presented by Clutter and Jones include slash pine plantations from south Georgia and north Florida through the Gulf Coast of Alabama and Mississippi. Utilizing their stand structure projection algorithm, thinning decreased cubic foot volume while increasing board foot volume production. Total board foot yield of thinned stands increased with earlier thinning ages, increasing thinning intensity, increasing site index, and lower initial densities. In an old-field loblolly plantation near Crossett, Arkansas having an initial density of 1,100 trees per acre at age 9, three intensive sawtimber treatments were established with an additional control thinned to 85 ft² of basal area at age 12 (Burton 1982). The sawtimber treatments were initially thinned to 100 trees per acre and repeatedly thinned at various intensities while the control was thinned to 85 ft² every three years. In addition to thinning, crop trees in the intensive treatments were pruned and understory vegetation was controlled beginning at age 19. Sawtimber volume first appeared at age 21 with the most intensive treatment (sawtimber only treatment) containing the most volume. By age 30, thinned treatments exceeded the standing volume existing on the control but no statistical difference was present among the
different intensively thinned treatments. When considering total sawtimber yield, conventional sawlog yield for the intensive treatments was 6.0, 2.4, 2.3, and 1.5 times that of the control at age 24, 27, 30, and 33 respectively. Parker (1979) reported that repeated heavy thinnings in old-field slash pine stands in Georgia to 50 square feet starting at age 12 reduced sawtimber volume at age 27 by 27%. The author did note that a single heavy thinning to 50 square feet did increase sawtimber volume at age 27 by 17%.

A board foot yield model for thinned old-field loblolly pine plantations in Virginia was developed by Burkhart and Sprinz (1984) using Bennett’s (1975) original form for slash pine. The yield model predicts board foot volume per acre as a function of total stand basal area and stand cubic foot volume.

Published reports on thinning studies for cutover plantations have been concentrated in the West Gulf region with most studies having initial stand densities near 700 trees per acre. The age at thinning varied from 17 to 20 years. In these studies, board foot volume yield increased inversely with thinning intensity between 70 to 100 square feet of residual basal area. Most thinning treatments involved multiple thinnings to a specified residual density on 5-year intervals. In a loblolly pine plantation in central Louisiana (Mann and Feduccia 1976) stands were thinned at age 20 and at 5-year intervals to several residual basal area treatments. Sawtimber yield at age 30 was only 800 bd.ft. less in unthinned plots than in plots repeatedly thinned to 100 square feet of basal area. However, by age 45 volume in the unthinned plots was 2,500 bd.ft. less than this treatment. Slash pine in this same study, thinned at age 17, exhibited similar yields that were inversely proportional to thinning intensity with the 100 square foot treatment having approximately 2,500 more bd.ft. than the unthinned check plots at age 32. Enghardt and Mann (1972) reported similar results for 27 year-old slash pine plantations initially thinned at age 17 in this same region. The largest board foot volume was associated with plots thinned to 85 square feet of basal area per acre (6,611 bd.ft.) and least in the unthinned plots (4,850 bd.ft.), although differences existed in initial plot volumes. On cutover flatwood sites in the West Gulf region,
slash pine thinned at age 17 had total yields at age 37 that were larger than the unthinned plots in all but the most heavily thinned treatments (Feduccia 1979). The largest standing board foot volume and net yield at age 37 was for those stands lightly thinned to a residual basal area of 100 square feet and the treatment thinned initially to 95 square feet and then maintained at 115 square feet at 5-year intervals. For plots thinned to a constant basal area, an average increase of 1,795 board feet was obtained for each 15 square foot increase in residual basal area. Thinning stands to less than 85 square feet reduced standing volume below that obtained for unthinned plots though net yield was greater in all but the most heavily thinned treatments. In a combined thinning and spacing study for loblolly pine in Louisiana (Woodworth spacing and thinning study), Feduccia and Mosier (1977) reported on total yield of sawlog volume through age 45. Board foot volume yield increased directly with increased spacing and indirectly with thinning intensity. Only the medium (70 ft$^2$) and light (100 ft$^2$) thinning intensities on the 10 X 10 foot spacing treatment contained more board foot volume than the unthinned control at age 45.

**Types of Thinning**

Thus far this review has concentrated on the individual stand response parameters with respect to thinning intensity. Equally important is how the thinning is conducted. Historically, thinnings in the South can be categorized as row or corridor thinnings where every $n^{th}$ row is removed to obtain a specific residual density either in a single thinning or multiple thinnings over time or selective thinnings where trees throughout the stand are removed usually on the basis of their inherent low vigor, age and/or form. Most selective thinnings reviewed can be classified as thinnings from below that primarily remove the lower vigor trees in the smaller diameter classes plus those larger trees that are of poor form or heavily infected with fusiform rust (*Cronartium fusiforme* Hedge and Hunt ex. cumm.). An interdisciplinary task force appointed by the
Southeastern Area of the U.S. Forest Service's State and Private Forestry concluded that individual tree selection was the best method of thinning from a silvicultural point of view but that the need for fire protection, the shortage of professional help, and the need to further mechanize harvesting techniques "would make selection thinning impossible if not uneconomical for many areas of the South" and thus recommended the application of row thinning (Anonymous 1971). The affinity to row thinning has been based on the perception that it is more economical since it lends itself to mechanized harvesting techniques. Minimization of cost is only half the picture. A thorough evaluation of stand growth and quality under different thinning types for all wood products is necessary to adequately evaluate the value of thinnings. There is evidence that selectively thinned stands have significantly higher volume, basal area, and diameter growth rates than row thinned stands (Cremer and Meredith 1976, Belanger and Brender 1968, Baldwin et al. 1989).

In most thinning studies reviewed, thinning experiments represented single plantations, localized geographic areas, limited age distributions and/or a limited range of planting densities, while generally confounding thinning intensity with type of thinning (Mann 1952, Williston 1967, Keister et al. 1968, Grano 1971, Cremer and Meredith 1976, Brendenkamp 1984). Only one study, though limited in geographic distribution, was designed to evaluate both alternative thinning intensities and type of thinning over a range of site indices, planting densities and age at first thinning without confounding intensity and thinning type treatments (Baldwin et al. 1989). In this study of both loblolly and slash pine plantations in central Louisiana, six thinning treatments and an unthinned control were established at each of six plantations. The thinning treatments included thinning every other row, every third row, and every fourth with the center row of the remaining three rows cut 5 years later. Selective thinning treatments were cut to within ± 3.01 square feet per acre of the residual basal area of the corresponding row thinned treatments. No statistical differences between selective and row thinned treatments in net inside bark volume and net basal area were found in either species immediately following the initial
thinning although expectedly, selectively thinned treatments had larger quadratic mean diameters and fewer surviving trees per acre. After 10 years, the selectively thinned stands had greater volumes with the difference being greater for slash pine (22%) than for loblolly pine (9%). Average basal area was 6% higher in selectively thinned loblolly plantations and 13% higher for slash pine. Average annual mortality (trees per acre) for both species was significantly higher in all row thinned treatments, as were losses in basal area and volume. Net periodic basal area and volume growth for selectively thinned stands were 50% and 80% higher for loblolly and 19% and 50% higher in slash pine, respectively. When comparing the average thinned stand to the unthinned control over the 10 year period, basal area growth was greater for both species in thinned than in unthinned stands while volume growth was slightly higher in unthinned loblolly stands with an even greater difference in slash pine. Both species had less mortality with respect to number of trees, basal area and volume in thinned than in unthinned stands.

A third thinning category, the combination of row and selective thinning techniques, has been tested to a limited extent with radiata pine in Australia (Cremer and Meredith 1976) and in loblolly pine in South Africa (Brendenkamp 1984). It has also been suggested for use in Southern plantations (Bennett 1971). This combination approach removes rows or corridors at predetermined intervals and selectively thins the adjacent residual rows. Whether this technique can combine the economic advantages associated with mechanized row thinning and the silvicultural advantage of selective thinning has yet to be proven experimentally in Southern plantations (Bailey and Pienaar 1982). However, results from radiata pine in Australia (Cremer and Meredith 1976) do indicate that combination thinning techniques had larger mean basal area and volume growth rates and equal mortality rates when compared with similar selectively thinned treatments on good sites.
Effect of Thinning on Tree Quality

The effect of thinning on residual tree quality has not been thoroughly tested in Southern pine plantations and still provides an avenue for debate. Measures of quality that have been reported in the literature include the proportion of sawlog volume by log grade (Mann 1952), tree form expression (Bassett 1966, Williston 1967, Keister et al. 1968, Burton 1982), length of clear bole (Bassett 1966, Burton 1982) and changes in tree juvenile wood production and specific gravity (Keister et al. 1968, Clark and Saucier 1991).

Bennett (1971) views thinning as secondary to initial spacing as a method for controlling the development of larger trees in a shorter time period. He reported (1969) that close spacings in slash pine are not necessary to produce timber that qualify as dense structural material on the basis of ring count and that the knotty core for trees in more dense stands do not differ greatly from those grown at 400 trees per acre. However, Ware and Stahelin (1948) report that "Plantations spaced at 6 X 6 feet or closer and thinned at age 12 to about 500 trees per acre left a stand equal in quantity and far superior in quality to unthinned 8 X 8 or 10 X 10 plantations."

Feduccia and Mosier (1977) noted that large loblolly pine stems could be produced at an early age at 10 by 10 foot spacings but that this spacing produced limby trees with stems that were lower in quality that other treatments.

Little experimental evidence is available to quantify the effects of thinning on resultant sawlog grade. Mann (1952) did report that unthinned loblolly pine stands had more Crossett Sawlog Grade 2 logs than either the crop tree or light thinning from below treatments. The treatment leaving 100 crop trees per acre resulted in the poorest quality trees. Thinning from above did provide 50% more Grade 2 logs than the light thinning from below. No other studies reviewed reported on sawlog yield by grade.

Tree form has also been reviewed and generally found to be unaffected by thinning (Bassett 1966, Williston 1967, Burton 1982). Keister et al. (1968) reported that thinned stands had higher Girard form class values than unthinned stands but that these differences
were slight. Bassett (1966) also reported that the length of clear bole was unaffected by thinning.

Another major concern is the specific gravity and the proportion juvenile wood present in trees following thinnings. Keister et al. (1968) noted that thinning did not alter the specific gravity of the outermost 10 inches of the stem when sampled at dbh. These findings from a single location are supported by Clark and Saucier (1991) who found that differences in geographic location greatly influenced the period of juvenile wood production and wood specific gravity. Spacing was also found to influence specific gravity with trees planted at wider spacings containing a smaller percentage of latewood and having lower specific gravity. However, the only statistical difference occurred in slash pine mature wood specific gravity between the 6 by 6-foot and 15 by 15-foot spacings. Cultivation and fertilization in plantations in the Gulf Coastal Plain did not significantly increase the length of the juvenile period for loblolly or slash pine and had no effect on juvenile or mature wood specific gravity. These authors suggest "by planting close and thinning after the trees are producing mature wood, resource managers can minimize the diameter of the juvenile core and reduce branch knot size."
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