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

PLANTATION MANAGEMENT RESEARCH COOPERATIVE

D. B. WARNELL SCHOOL OF FOREST RESOURCES
UNIVERSITY OF GEORGIA
ATHENS, GEORGIA 30602

PREPARED BY

John R. Brooks

Robert L. Bailey

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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 ft^2 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 ft^2 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 ft^2 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 ft^2 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 ft^2 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:

$$\mathrm{Log(CR)} = 2.40054 - 0.20669\ \mathrm{Log(Density)}$$

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:

$$\frac{1}{N}\frac{\partial N}{\partial A} = \alpha A^{\gamma} N^{\varphi}$$

and has the form :

$$N2 = [N1^{\alpha_1} + \alpha_2 (A2^{\alpha_3} - A1^{\alpha_3})]^{\frac{1}{\alpha_1}}$$

where:

N_i = 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:

$$N2 = N1\left(\frac{A2}{A1}\right)^{\beta_1} \mathrm{Exp}\left\{ (\beta_0 + \beta_2\, SI)(A2 - A1) + \beta_3 * Xt * Z\left(\frac{\left(\frac{1}{A2} - \frac{1}{A1}\right)}{At} \right) \right\}$$

where:

Z = 1 if $A2 < 22.5$
0 if $A2 \geq 22.5$

Xt = the ratio of the quadratic mean diameter of the trees removed in thinning to the quadratic mean diameter of the whole stand before thinning

At = age of stand at last thinning

N_i = number of trees surviving per acre at age i

A_i = stand age at time i

S = 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:

$$N2 = N1 * \mathrm{Exp}\left\{ \beta_1 \left(\left(\frac{A2}{10}\right)^{\beta_2} - \left(\frac{A1}{10}\right)^{\beta_2} \right) \right\}$$

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:

$$N2 = \left\{ N1^{\beta_1} + \left(\beta_0 + \frac{\beta_2}{S}\right)\left[\left(\frac{A2}{10}\right)^{\beta_3} - \left(\frac{A1}{10}\right)^{\beta_3} \right] \right\}^{\frac{1}{\beta_1}}$$

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:

$$\mathbf{N2} = \mathbf{100}\left[\left(\frac{\mathbf{N1}}{\mathbf{100}}\right)^{\beta_1} + \left(\beta_2 + \frac{\beta_3}{\mathbf{SI}}\right) * \left(\left(\frac{\mathbf{A2}}{\mathbf{10}}\right)^{\beta_4} - \left(\frac{\mathbf{A1}}{\mathbf{10}}\right)^{\beta_4}\right)\right]^{\frac{1}{\beta_1}}$$

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:

$$\mathbf{Y} = \alpha_0(\mathbf{A1}-\mathbf{A0})^{\alpha_1}\left(\frac{\mathbf{N0}}{\mathbf{B0}}\right)^{\alpha_2}(\bar{\mathbf{H}}\mathbf{0})^{\alpha_3}\,\mathbf{Exp}\left\{\alpha_4\,\mathbf{B0} + \alpha_5\left(\frac{\mathbf{B0}}{\mathbf{A0}}\right) + \frac{\alpha_6}{\mathbf{A0}}\right\}$$

where:

Y = the number of trees dying per acre from A0 to A1
$\bar{H}0$ = Average height of dominants and codominant at A0
B0 = initial stand basal area per acre
A0 = initial age
A1 = projection age
N0 = initial trees per acre
N1 = 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:

$$\mathbf{N2} = [\, \mathbf{N1}^{\beta 1} + \beta_2 * (\, \mathbf{A2}^{\beta_3} - \mathbf{A1}^{\beta_3}\,)\,]^{\frac{1}{\beta_1}}$$

where:

Ni = plantation survival at age i
Ai = 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 ft^2/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:

$$\mathrm{Ln}(B2) = \left(\frac{A1}{A2}\right)^{\beta_1} \mathrm{Ln}(B1) + \beta_2\left[1 - \left(\frac{A1}{A2}\right)^{\beta_1}\right]$$

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: