Chapter 8

Longleaf Pine Growth and Yield

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Introduction

Across the historical range of longleaf pine (*Pinus palustris* Mill.), less than 10% of lands previously occupied by longleaf ecosystems are currently in public ownership (Johnson and Gjerstad 1999; Alavalapati et al., this volume). The remainder is owned by private entities ranging from the forest industry, to timberland investment organizations, to highly varied nonindustrial private landowners. Any significant recovery of longleaf is therefore dependent on the participation of the private sector. Certainly, for the forest industry, and many other investor-type groups, the need for competitive returns from forest management is extremely important. And although experience has indicated that economic return is often not the primary motivator for nonindustrial landowners, it usually plays some role in management decision-making.

One major area requiring more knowledge is the need for models to reliably project growth and, ultimately, economic value of longleaf pine. Some limited data are available for projecting natural stands of longleaf that may be extrapolated to yield estimates of potential growth in planted stands, but there is a great deal of uncertainty when gains in seedling quality, competition control, fertilization, and other silvicultural techniques are factored in. Much of the reestablishment of longleaf pine taking place today is occurring on old fields and pastures. At least half of that planted is done so using containerized seedlings, usually employing both intensive site preparation and follow-up herbaceous competition control to improve survival and accelerate growth.

Longleaf pine can grow competitively with, or even exceed, the growth of other southern pine species on many sites. If markets continue to award quality wood products, particularly utility poles, with premium prices, longleaf is highly competitive. Private industrial and nonindustrial landowners should therefore respond positively to that possibility and make longleaf a vital part of their portfolio.

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Historical Perspective

The first European explorers to visit the southeastern U.S. Coastal Plain found a vast parkland of low ground cover growing under a relatively open canopy of pine (Bartram 1791; Schwarz 1907). Depending on the geography and/or soils, the dominant tree was longleaf pine.

Schwarz (1907) noted that within pure stands of longleaf pine, certain minor variations existed. The most important variation was in the density of trees. Ordinarily, the stand of trees did not maintain uniformity over more than a few hundred acres; often changing abruptly even within 50 acres. Schwarz (1907) gave this description:

> Thus we may enter a stand of mature timber, with trees from 90 to 120 feet in height and with ample spaces here and there in the crown cover, giving entrance to the light from overhead. After walking perhaps only a few hundred paces, we may find the trees suddenly beginning to close up their crown spaces. They grow smaller and more numerous, until presently they form a tolerably dense grove; and then they open up once more into the original stand of mature, tall trees. Occasionally, too, a tract of old trees of fairly uniform height is replaced by one in which the trees show diversity in size, ranging from mere poles to veterans of the forest.

Although an extremely intolerant tree, which will thrive best in even-aged stands, the natural form of longleaf pine tends toward small, even-aged groups of a few hundred square feet. Being naturally resistant to fire, large clearings are never caused by fire. In regions of severe winds, or tornadoes, larger even-aged patches and strips are found, sometimes one-quarter to one-half mile in width, which have come in after blowdown. These are pretty well interspersed with patches or single survivors of the old forest, which have acted as seed trees. Fire always has and always will be an element in longleaf forests, and the problem is not how fire can be eliminated but how it can be controlled so as to secure reproduction; second, to prevent the accumulation of litter and reduce the danger of a disastrous blaze. The factor that probably determines growth and yield is root competition for soil moisture. Longleaf stands are subject to severe droughts. The slow juvenile growth and long taproot of the young tree indicate its adaptation to this condition. Very young stands of longleaf may be quite crowded and remain so for 50 to 80 years. But it was found that such stands, if closely crowded, fell off in growth so badly that there was a distinct loss of production. Trees less than 100 years of age continued to grow vigorously in diameter even in rather dense groups, provided such groups were isolated and did not form a complete stand. But above this age it was found that groups of several trees standing close together would have differentiated themselves into dominant and suppressed trees, one or two trees with large crowns showing continued growth, while the rest were almost stationary. These occurred in groups surrounded by open space and could not be accounted for by struggles for light. Root competition alone can account for the thinning out of mature longleaf forests and the wide spacing of veteran trees. It also accounts, to a greater extent than intolerance, for the absence of seedlings under the open crowns of veteran trees, and their appearance only in openings at some distance from such trees. The indicated management for longleaf pine is to avoid crowding and not to attempt rotations much longer than 100 years or the production of large sizes. The ideal form for young stands of longleaf would be to have them stocked at most with only about twice as many saplings as should be standing in the form of mature trees at the end of the rotation.

It is evident that under natural conditions, even in the presence of repeated fires, the longleaf pine forest renews itself, young trees coming in on areas left blank by the death of old timber. All trees in a stand do not grow equally fast, nor continue to grow at the same rate. In longleaf pine this is especially noticeable. Only the largest trees, with the biggest crowns, continue to grow at a rapid rate after a stand has reached merchantable size. After a longleaf pine stand reaches the age of about 120 years, the loss from red rot, fire, and suppressed growth increases so fast that the net gain in growth on the stand would not pay the taxes. This slow destruction of timber that offsets growth is due chiefly to the inability of the soil to support so many trees of large size.

Old Growth Information from the Literature

Based on timber tallies of 162 ha (400 acres) of pure even-aged, old-growth longleaf pine stands in Tyler County, TX, Chapman (1909) found that trees per hectare dropped from 148 to 27 (60 to 11 trees/acre) going from a stand 100 years old to 320 years old with average diameter at breast height (DBH) increasing from 37.0 to 77.9 cm (14.0 to 29.5 in.). Mean annual growth [in thousand board feet (MBF) per acre per year] reached at a maximum at 110 years. This indicated that longleaf pine does not increase much in yield after 120 years with the increase in mortality due to decay, fire, and other disturbances. The increase in total yield is very slow up to 250 years and then diminishes. Trees less than 100 years old will grow vigorously in diameter even in rather dense stands provided groups are isolated and do not form a complete stand.

Wahlenberg (1946) noted that old-growth forests were aggregations of even-aged stands covering areas from a few hundred square feet to several acres. Well-stocked stands had 74 to 247 merchantable trees/ha (30 to 100 trees/acre), and poorer sites as few as 5 to 7 trees/ha (2 to 3 trees/ha). Using data from Forbes and Bruce (1930), Wahlenberg (1946) observed that over wide regions of the South, the forest contained many age and size classes of trees, with only small areas usually limited to a single age class.

Growth and Yield of Natural Stands

There has been a great deal of research on the growth and yield of longleaf pine. Farrar (1979a) published the first growth and yield equations for thinned stands of even-aged natural longleaf pine. Uneven-aged stands are more complex structurally and thus more difficult to model.

Other attempts at predicting growth have involved the use of empirical yield tables, which are direct estimates of growth based on stand structure and volume tables. Davis (1966) indicated that good estimates of growth should provide growth directly in hectares, include the fewest possible variables, require a minimum of field data, provide estimates in cubic foot volume, do not use age as a primary variable, and treat height growth differently than diameter growth.

Spurr (1952) proposed a method to account for diameter growth and height growth in projecting volume growth. One must first be able to predict basal area and tree height growth. Growth in basal area is largely a function of stand density while height growth is primarily a function of site quality and stand age. Once basal area and height measurements are estimated and volume calculated for the present stand, then estimates of volume for some future stand can be calculated. Assuming the stand form factor remains unchanged, the relationship between the product of basal area and height (for a given volume) will hold for the future period, i.e.,

$$\frac{PBA \times PHt}{P\ Vol} = \frac{FBA \times FHt}{F\ Vol}$$

where

PBA is the present basal area
PHt is the present height
P Vol is the present volume
FBA is the future basal area
FHt is the future height
F Vol is the future volume

The difference between future volume and present volume is the increment of growth for the period.

Another approach is to use a stand, or stock table, projection. The essence of a stand table projection is to estimate the future stand based on the present one. The problem is what diameter increment to use and how to apply the expected growth to the diameter class. Diameter increment data could be added to the midpoint of the diameter class. This method assumes that all trees in a given diameter class are at the midpoint and grow at the same rate. This assumption reveals the limitation of this method of predicting stand growth as all trees in a given diameter class will not be the same size and all trees will not be at the midpoint of the diameter class.

A second method applies the average diameter growth to all trees within a class while recognizing dispersion of individuals within the same class. This method uses a movement ratio technique to predict what percentage of trees within a diameter class move up into larger diameter class, and what percentage will remain in the same diameter class. The movement ratio is defined as

$$M = (g/i) \times 100$$

where

M = movement ratio
g = diameter growth increment
i = diameter class interval

For example, assume the average diameter growth was 5.3 cm (2.1 in.) over a period of time, and the diameter class interval is 5 cm (2 in.), then the movement ratio is calculated to be 105. This means that 5% of the trees move up two diameter classes while 95% of the trees move up only one diameter class.

Growth and yield models have been developed for uneven-aged stands of loblolly and shortleaf pines (Farrar et al. 1984; Murphy and Farrar 1985). Some general inferences from these studies conducted in Arkansas were that loblolly and shortleaf pine average annual growth could be expected to be around 0.3 m^2 (3 ft^2) of basal area and 2.4 to 3.3 m^3 (84 to 116 ft^3) of merchantable volume growth. Volume growth on the Mississippi study locations showed slightly lower production compared to the Arkansas sites (Baker et al. 1996).

Farrar (1996) provided guidelines for the uneven-aged management of longleaf pine. Nature managed longleaf pine as small patches of even-aged stands across an uneven-aged landscape. The main drawback with uneven-aged management with longleaf pine is that a lot of work is required to keep up with how a stand is growing. The fact that it takes a considerable amount of work to manage longleaf pine under an uneven-aged system has discouraged past management of longleaf pine in this way. However, recently public agencies such as state forest divisions or departments and the USDA Forest Service are attempting to manage longleaf pine using the uneven-aged silvicultural approach.

The best estimate of longleaf pine growth and yield for natural stands can be found in Farrar (1979b). The USDA Forest Service established a regional longleaf pine growth study (RLGS) in the mid-1960s in southwest Georgia, northwest Florida, southern Alabama, and southern Mississippi. The data from this study and the subsequent formulas represent the net volume growth and yield one might expect in the absence of adverse influences such as weather, insects, and disease. The equations for estimating growth and yield (inside bark) of thinned natural longleaf pine are given below (the symbols and letters follow throughout all of the formulas).

Basal area is calculated as

$$\mathrm{BA} = 0.2296 B_2$$
$$B_2 = e[(A_1/A_2)\ln(B_1) + 6.0594(1 - A_1/A_2)]$$

where

BA = projected basal area at the end of the period in square meters per hectare
B_2 = projected basal area at the end of the period in square feet per acre
e = exponential function
A_1 = initial stand age in years (beginning of the period)
A_2 = stand age at the end of the period in years
ln = natural logarithm
B_1 = initial basal area in square feet per acre

Total volume is given by

$$\mathrm{TVIM}_2 = 0.06997\ \mathrm{TVI}_2$$
$$\mathrm{TVI}_2 = e[2.6776 + 0.015287(S) - 21.909/A_2 + (A_1/A_2)\ln(B_1) + 6.0594(1 - A_1/A_2)]$$

where

$TVIM_2$ = projected stand total volume, inside bark, in cubic meters per hectare at the end of the period, DBH $\geq$ 1.5 cm (0.6 in.), 6.1-cm (0.2 ft) stump, S = site index in feet, base age of 50 years
TVI_2 = projected stand total volume, inside bark, in cubic feet per acre at the end of the period

When $A_1 = A_2$ and $B_1 = B_2$ or the growth period is 0, then the above equation can be reduced to

$$\text{TVIM} = 0.06997\ \text{TVI}$$
$$\text{TVI} = e[2.6776 + 0.015287(S) - 21.909/A + \ln(B)]$$

where A, S, and B are current stand age, site index, and basal area, respectively, TVIM is the predicted current stand volume in cubic feet per hectare, and TVI is the predicted current stand volume in cubic feet per acre.

The equation for calculating the predicted stand total volume (outside bark) is

$$\text{TVOM} = 0.06997\ \text{TVO}$$
$$\text{TVO} = \text{TVI}\ [1 + e\{-0.1785 + 43.629/S + 1108.6/(SB) - 0.42802(\ln(A)) - 360.87(\ln(A))/(SB)\}]$$

where

TVOM = cubic meters per hectare
TVO = volume in cubic feet per acre

The above equation for calculating the total stand volume (outside bark) can be used for either the beginning or initial stand condition or the final condition using the appropriate TVIM, TVI, age, site index, and basal area figures.

Farrar (1979b) also published formulas to determine merchantable volumes for both present and future stands. The merchantable volume formula is

$$\text{V4IM} = 0.6997\ \text{V4I}$$
$$\text{V4I} = \text{TVI}/[1 + e\{2.623 + 316.77/S + (SB) - 2.8248(\ln(A)) - 3326.7(\ln(A))/(SB)\}]$$

where

V4IM = predicted stand merchantable volume in cubic meters per hectare, inside bark, DBH $\geq$ 9.1 cm (3.6 in.), top DOB (diameter outside bark) $\geq$ 7.6 cm (3 in.), 6.1-cm (0.2 ft) stump
V4I = predicted stand merchantable volume in cubic feet per acre

These formulas have their limitations. First, they were derived from the first 5 years of the study. Actual growth beyond 5 years has not been used to adjust formula coefficients. Indeed, the study report indicates that the estimates of total cubic foot volume provided the most reliable results while the formula for estimating merchantable volume was the least reliable. A second limitation is that these equations were derived for trees growing in stands that were thinned. These equations used trees from thinned stands, a 5-year growth period, and low mortality. Future yield predictions were also not reliable, and the estimates became unrealistically large for unthinned stands.

Even though the equations developed by the Forest Service and reported by Farrar (1979b) have their limitations, they do provide a useful estimate of a stand's volume and an estimate of the stand's future volume and basal area. Stand predictions of growth and yield are useful to landowners attempting to manage their forests.

Quicke et al. (1994) used the RLGS database and produced an individual tree basal area increment (BAI) model for longleaf pine. The model is an intrinsically nonlinear equation, which is constrained so that it performs within the bounds of biologically reasonable outputs for any combination of values for the independent variables. All parameters in the equation were estimated simultaneously. This is a departure from the more traditional potential-times-modifier approach in which parameters for a potential growth function are estimated from a sample of trees exhibiting the fastest growth. Independent variables used to describe BAI are stand basal area, the competitive position of an individual tree within the stand calculated as the sum of the basal areas of all trees larger than the subject tree, mean age of dominant and co-dominant trees, and individual tree diameter outside-bark at breast height. Noticeably absent from the model is an independent variable that explicitly characterizes site differences.

Further work by Quicke et al. (1997) created an individual tree annual survival rate model. Variables used in the model were predicted diameter increment and diameter at breast height (DBH). Predicted annual survival rates ranged from 0.92 for a tree with a 2.54 cm (1 in.) DBH and an annual diameter increment of 0.13 cm, to over 0.99 for any tree larger than 15 cm in DBH. Stand level verification was based on 102 comparisons of observed and predicted trees per acre. Mean residuals, expressed as a percentage of observed final trees per acre, were 3% and 6% for projection periods of 5 and 10 years, respectively. The model predicts noncatastrophic mortality. In conjunction with a basal area increment model, it can be used to predict changes in the structure of longleaf pine stands. Meldahl et al. (1997) used the RLGS dataset to calculate needle fall, standing biomass, net primary productivity, and projected leaf area. In addition, climatic variables were included in tree and stand models.

Another study by Saucier et al. (1981) developed weight, volume, board-foot, and cord tables for major southern pine species, including longleaf pine. Data for this study were derived by felling sampled trees and measuring diameter, total height, and height to various merchantability limits.

The equation for predicting the total tree green weight using DBH and total height is

$$YM = 0.4536\,Y$$
$$Y = -44.418879 + 0.20297(D^2Th)$$

where

YM = total tree weight in kilograms
Y = total tree weight in pounds
D = DBH in inches
Th = total height in feet

The total tree green weight to a 10.2-cm (4 in.) top is given by

$$YM = 0.4536\,Y$$
$$Y = -36.83043 + 0.15608(D^2Th)$$

The study gives the cubic foot volume of the stem to a 10.2-cm (4 in.) top as

$$VM = 0.2832\,V$$
$$V = -0.84281 + 0.02216(D^2Th)$$

where

VM = volume in cubic meters
V = volume in cubic feet

For longleaf pine, the paper also gives green weight to 17.8-cm (7 in.) and 22.9-cm (9 in.) tops; green weight of wood, bark, and foliage; wood volume to 17.8- and 22.9-cm tops; board foot (Scribner) volumes; green weight of sawtimber per MBF; and pulpwood weights and volumes.

Growth and Yield of Planted Stands

The most broadly based system of stem profile equations (and hence volume) is provided by Clark et al. (1991). Clark et al. (1991) include equations to predict stem diameter at any height, given diameter at breast height and at Girard's Form Height (5.3 m or 17.3 ft), total height, and the height at which diameter is to be predicted. The equations can also be used to estimate height at a given minimum diameter (merchantable height), and volume in cubic feet to any minimum diameter, or volume between a maximum and minimum diameter (such as pulpwood volume above sawtimber volume). There also are equations to use if height to a top diameter, rather than total height, is known. If diameter at form height is not measured, Clark et al. give an equation to predict it from diameter at breast height and total height. Bark thickness at breast height can also be estimated from an equation that predicts diameter inside bark. Clark et al. furnish parameter estimates for longleaf pine that represent South-wide estimates as well as subregions, namely, Coastal Plain (Atlantic coast and eastern Gulf—Alabama and points east and north), Piedmont (all states), and Deep South (Texas, Louisiana, and Mississippi).

Thomas et al. (1995) provide biomass and taper equations for longleaf pine in thinned and unthinned plantations in Louisiana and Texas. Their taper equation predicts upper stem diameters as a function of relative height, diameter at breast height, and plantation age. Volume is obtained by the integral of the taper equation, between limits of merchantability. Weight of the bole is obtained by doubly integrating (across diameter and height) a function for specific gravity. However, their equation for specific gravity was unique for the ages of the sampled trees (35, 45, or 50 years), and thus has somewhat restricted applicability. Thomas et al. compared their taper equations for four classes of stands: (1) an unthinned Louisiana plantation; (2) a thinned Louisiana plantation; (3) a different thinned Louisiana plantation and two thinned Texas plantations; (4) natural and plantation-grown longleaf from various stands in Alabama. These four classes produced taper equations that differed; the Alabama taper curve was particularly different from the others. This suggests that site and management differences can have large effects on stem taper. If stem taper varies so much from stand to stand, this suggests that regional volume equations will be poor estimators for any given stand, unless the volume/taper equation includes some measurement of form beyond simply measuring diameter at breast height and total height. This suggests that Clark et al. (1991), with diameter at form height determined from local data, would be preferable to regional volume equations. Clark et al. (1991) can be applied to natural and planted longleaf, and they have estimated their equation for all common species or species groups that are associates of longleaf pine.

Baldwin and Polmer (1981) used data from some of the same plantations as Thomas et al. (1995). They fit three different taper equations for different classes of crown ratio (less than 36%, between 36% and 50%, and greater than 50%). Crown ratio potentially can reflect the differences in taper among trees within and among stands. Even when crown ratio is not measured on every tree, it should be possible to assign crown ratio class reasonably accurately to trees as height is measured. These taper and volume equations should be useful for estimating volume in longleaf pine stands in the western Gulf states (Texas and Louisiana). Brooks et al. (2002) provide taper and cubic foot volume equations for young plantations in southwest Georgia; they compared their equations to the equations of Baldwin and Polmer (1981) and Baldwin and Saucier (1983), but they did not measure crown ratio, and so could not fully utilize Baldwin and Polmer's (1981) equations. The taper equation of Brooks et al. (2002) was slightly superior to that of Baldwin and Polmer (1981), and their volume equation was slightly superior to those of Baldwin and Polmer (1981) and Baldwin and Saucier (1983); however, this is expected because they used the same data to fit and test their equation, while the Baldwin equations were fit to other data. It is reasonable to expect bias when an existing equation is applied to a new dataset that is geographically distinct from the data on which the equation was estimated. However, the bias was not large, and when the bias was made equal to the bias of the equation of Brooks et al. (2002), the taper equation of Baldwin and Polmer (1981) would have produced lower absolute error than the equation of Brooks et al. (2002) (calculations by the second author). This suggests that Baldwin and Polmer (1981) might be more broadly applicable than Brooks et al. (2002).

Baldwin and Saucier (1983) provide aboveground weight and volume estimators for unthinned planted longleaf pine, using 111 of the 113 trees sampled in Baldwin and Polmer (1981). Rather than using a taper equation, they used a combined variable equation (Clutter et al. 1983) given by

$$\log(Y) = b_0 + b_1 * \log(D^2 H)$$

where Y is either volume or some biomass component, D represents diameter at breast height, and H represents total height. To estimate volume to some minimum top diameter, they estimate a volume ratio equation that is multiplied by the value for total volume. As they did not use any variable, such as crown ratio, that could explain stand-to-stand and tree-to-tree variability in taper, we suggest the taper equations of Baldwin and Polmer (1981) would be preferable for estimation of volume. However, Baldwin and Saucier's (1983) biomass equations are probably the only regional equations to estimate green and dry weight of wood, bark, branches, and foliage, given the limitations in application of the bole biomass equations of Thomas et al. (1995). There are biomass equations for longleaf in very young natural stands (presumably natural stands, the publication only indicates they are even-aged; Edwards and McNab 1977) and an old natural stand (Taras and Clark 1977). The results of Taras and Clark (1977) are included in USDA (1984) tables.

To estimate board foot volume, there are a few different approaches. The first approach is to use volume tables derived from natural stands, such as those found in USDA (1929). These volume tables use diameter at breast height and total height to predict board foot volume by several different log rules. The second approach employs form class volume tables, such as Mesavage and Girard (1946). Wiant (1986; Wiant and Castaneda 1977) created equations that approximate the Mesavage and Girard (1946) tables for form class 78 (form class is diameter inside bark at 17.3 feet height divided by diameter outside bark at breast height). Use of the equations may be more efficient for some individuals than looking up the values in a table, although the table look-up can be programmed. Wiant (1986) assumed a 3% change in volume for each point of form class change from 78 (higher volumes would be obtained with higher values of form class). A landowner may have a good idea of the form class for his holdings, perhaps as a function of diameter and height of the tree. Alternatively, Clark et al. (1991) have an equation for diameter inside bark at 5.3 m (17.3 ft). Because of the structure of the equation, form class is a constant for a given total height; that is, diameter at breast height does not affect form class. This is counterintuitive, as it would seem likely that form class should depend on diameter and height, but the relationship seems to hold for the data of Clark et al. (1991). The corresponding form class produced by their equation is provided in Table 1. On the other hand, Parker (1998) suggests that taper could be constant within diameter classes rather than height classes. The taper equations of Thomas et al. (1995) suggest that form class varies in response to diameter, height, and age, and does so differently for thinned and unthinned stands. Age has a relatively small difference on taper, but DBH and height have

TABLE 1. Form class (in percent) by height relationships for three subregions and South-wide, as calculated from an equation of Clark et al. (1991)

	Total height (ft)								
Region	40	50	60	70	80	90	100	110	120
South-wide	66	73	77	79	81	82	83	83	84
Coastal Plain (AL to VA)	67	73	77	79	80	81	82	82	83
Piedmont	65	73	77	80	81	82	83	84	84
Deep South (TX, LA, MS)	62	72	77	80	83	84	85	86	86
	Total height (m)								
Region	12.2	15.2	18.3	21.3	24.4	27.4	30.5	33.5	36.6
South-wide	66	73	77	79	81	82	83	83	84
Coastal Plain (AL to VA)	67	73	77	79	80	81	82	82	83
Piedmont	65	73	77	80	81	82	83	84	84
Deep South (TX, LA, MS)	62	72	77	80	83	84	85	86	86

Table 2. Form class (in percent) at age 40 related to diameter (DBH) and total height for thinned and unthinned stands in Louisiana and Texas, calculated from taper equation of Thomas et al. (1995) and bark thickness equation of Clark et al. (1991)

DBH (in.)	Height (ft)	Thinning	Form class
9	50	Thinned	74
9	80	Thinned	81
12	50	Thinned	75
12	80	Thinned	82
9	50	Unthinned	73
9	80	Unthinned	79
12	50	Unthinned	74
12	80	Unthinned	80
DBH (cm)	Height (m)	Thinning	Form class
22.9	15.2	Thinned	74
22.9	24.4	Thinned	81
30.5	15.2	Thinned	75
30.5	24.4	Thinned	82
22.9	15.2	Unthinned	73
22.9	24.4	Unthinned	79
30.5	15.2	Unthinned	74
30.5	24.4	Unthinned	80

a larger effect (Table 2). There are relatively small differences in absolute numbers between Tables 1 and 2. However, there are fundamental differences in the choice of the factors that affect form class. This could be very important when contrasting different silvicultural practices. If silvicultural practices affect form class, the chosen equation might not reflect those differences and thus the real difference among treatments might not be apparent.

The values in Table 1 can be used in concert with Mesavage and Girard's (1946) tables or Wiant's (1986) equation. Borders and Shiver (1995) used the taper equation of Clark et al. (1991) to produce board foot tables for loblolly, slash, and shortleaf pines. Their tables suggested greater volume than Mesavage and Girard (1946). This might suggest that Mesavage and Girard (1946) underestimate board foot volume for longleaf pine as well. Borders and Shiver (1995) present the final procedure for calculating board foot volume. They used a taper equation to calculate inside bark diameters at the scaling diameter of each log of fixed length, and directly applied their chosen log rule to calculate volume of each log. Any taper equation could be used in this way, although it is tedious if the calculations are done by hand rather than programmed. A program to calculate board foot volume in this way is available from the second author (jcgoelz@fs.fed.us) or from the programmer, Daniel Leduc (dleduc@fs.fed.us).

Poles are a high-value product, greatly exceeding the value of sawtimber per board foot, and thus it is critical to determine yield of poles. Any of the taper equations can also be used to determine whether a tree of a given diameter at breast height and total height possesses the minimum dimensions for top diameter and length of poles. ANSI (1987) provides specifications for dimensions of poles for 10 quality classes for pole lengths of 6.1 to 38.1 m (20 to 125 ft), in increments of 1.5 m (5 ft). The specifications are in terms of circumference (diameter times π) at 1.8 m (6 ft) from the butt of the pole. The taper equation can be solved for diameter at a height of 2.2 m (7.3 ft; counting stump and sawkerf). Hawes (1947) assumed a constant ratio of diameter inside bark at a height of 1.8 m (6 ft) to be 0.88 times diameter outside bark at breast height. Using taper and bark thickness equations would probably be more accurate for a specific tree. Quicke and Meldahl (1992) used a taper equation for natural longleaf to create such tables. Any taper equation and bark thickness equation for planted longleaf could be used in a similar fashion. The differences between the tables of Quicke and Meldahl (1992) and Hawes (1947) were greatest for long poles. Busby et al. (1993) found that 90% of trees in their plantations of longleaf pine in Louisiana were sufficiently free of defect to produce a pole if they met the diameter and length requirements.

Evaluating Site Quality

Site quality is a critical component of most growth and yield models. Lohrey and Bailey (1977) created a growth and yield model for unthinned plantations of longleaf pine. In it, they used the site index equations produced by Farrar (1973). Farrar (1973) developed his equations to reproduce the graphical site curves provided for natural second growth

Table 3. Number of trees (A) per acre and (B) per hectare to be planted to achieve thinning thresholds of GLSDI of 50% of maximum or 4/3 of crown closure for different levels of quadratic mean diameter and survival (to age of first thinning)

	90% survival		70% survival		50% survival	
DBH (in)	1/2 maximum	4/3 crown closure	1/2 maximum	4/3 crown closure	1/2 maximum	4/3 crown closure
4	1355	1014	1742	1303	2439	1824
6	604	463	777	595	1088	834
8	341	264	438	340	613	475
10	218	170	280	219	393	307
12	151	119	195	153	273	214
DBH (cm)						
10.2	3348	2506	4305	3220	6027	4507
15.3	1493	1144	1920	1470	2689	2061
20.4	843	652	1082	840	1515	1174
25.4	539	420	692	541	971	759
30.5	373	294	482	378	675	529

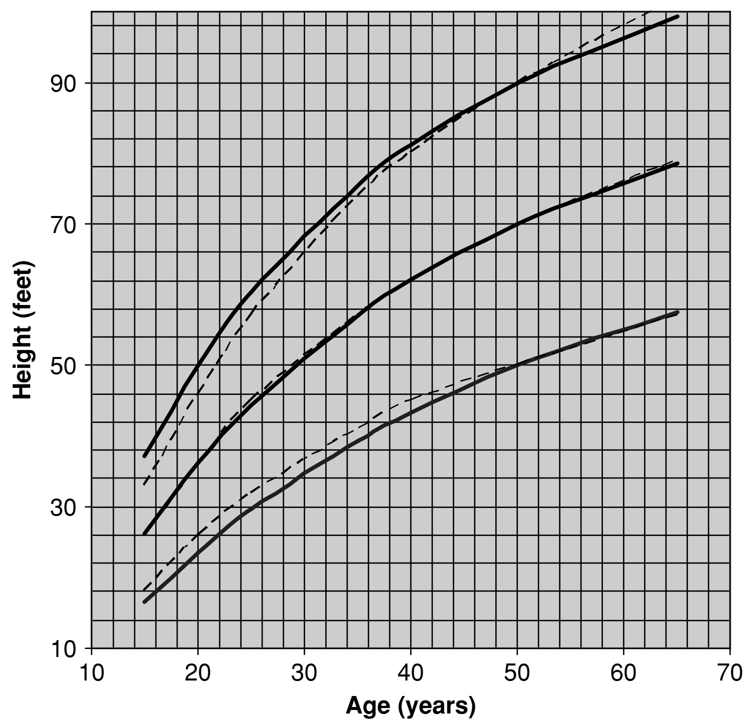
longleaf pine in USDA (1929). It should be noted that while the USDA (1929) curves indicate zero height before age 5, Farrar's (1973) curves are not conditioned in this way, and do not adequately represent the USDA (1929) curves at ages below 15 years. Apparently, Lohrey and Bailey (1977) found the curves for natural longleaf pine stands (USDA 1929; Farrar 1973) adequately represented the plantation grown longleaf data that they had available. Goelz and Leduc (2003) provided preliminary site index curves using the data of Lohrey and Bailey (1977), as well as additional measurements on the same plots, and supplemental plots that were not available to Lohrey and Bailey (1977). The curves of Goelz and Leduc (2003) are very similar to the USDA (1929) curves for site index of 70 at base age of 50 (Fig. 1). However, the curves for site index 50 and 90 are considerably different from the USDA (1929) curves. The anamorphic curves represented by USDA (1929) do not change shape as site index changes. There is a very common phenomenon that arises in polymorphic site index curves where the curves for the lower sites tend to be more linear while the curves for the higher sites tend to be more curved, achieving a higher proportion of the asymptotic height at younger ages (Goelz and Burk 1996). This expected pattern is missed in the anamorphic curves, but is obtained in the polymorphic curves of Goelz and Leduc (2003). Brooks (2004) describes an equation to predict dominant stand height for young longleaf plantations in southwest Georgia.

Boyer (1980, 1983) suggested that planting site (old field, unprepared cutover, mechanically prepared cutover) and stand density (survival at 10 years) affected early growth of longleaf pine. Boyer used a simple Schumacher equation:

$$\log_{10}(H) = b_o + b_1 \frac{1}{A}$$

to fit a common guide curve for all site conditions, where H and A represent height and age, respectively, and the b_i are parameters. Then, he expanded the equation by making b_1 a linear function of surviving trees per unit of land and height at age 15 (height at age 15 was only included for the two cutover sites). This structure produced site curves that are anamorphic for old-field situations and polymorphic for the two cutover situations and having a common asymptote for all combinations of site index and site condition. Although he labeled his curves by height at age 25, by including height at age 15 as a predictor variable, he was essentially creating base age specific site curves with 15 as the base age.

FIGURE 1. Comparison of site index curves from USDA (1929), dashed lines, and Goelz and Leduc (2003), solid lines, for site index (base age 50) of 50, 70, and 90 feet.



Goelz and Leduc (2004) suggested that a base age of 50 years provided more reliable estimates of site index than a base age of 25 years. The trade-off seems to be to either model this early height growth directly, or lose some of the capacity to define site quality, or to ignore the early, largely random variation and concentrate on the intrinsic productivity of the site. We suspect that the different bias of the perspectives of Boyer (1980, 1983) and Goelz and Leduc (2004) arises from the different natures of their datasets, predominantly 15 years or younger versus predominantly 16 years and older.

Shoulders and Tiarks (1980) produced regression models for planted longleaf pine in Louisiana and Mississippi relating height at age 20 to rainfall, slope, and available soil moisture (1/3 atmosphere percent minus 15 atmosphere percent) in the B2 horizon. Longleaf pine height was greatest where rainfall was least 122 cm (48 in.) per year (evenly split between warm season, April through September, and cool season), on very modest slopes (1.6%), and where moisture-holding capacity suggested loams or sandy loam soils (6–9%). Rainfall is clearly related to geography, and thus the effect of rainfall is confounded with soil differences and perhaps difference in constituents of the competing vegetation. Moisture-holding capacity affects competing vegetation, and thus the effect may be due to competition rather than moisture availability per se. An earlier analysis at age 15 (Shoulders and Walker 1979) suggested that the effect of rainfall was different on sites with droughty soils compared to wet or intermediate sites. Rainfall was positively related to height for droughty soils while negatively related to height for wet and intermediate sites. This suggests that aeration may be limiting to growth where soils may become saturated, but not on inherently dry sites. To estimate site index, a user could estimate height at age 20, using the equation of Shoulders and Tiarks (1980), then apply this height to a site index equation or curve.

Harrington (1990) produced an expert system to predict site index of both natural and planted longleaf pine from 25 soil and physiographic variables. Most of the variables need only be given qualitative values, or assigned to classes of continuous variables. A user can make reasonable guesses for the more difficult to measure variables, such as percent phosphorus, from soil survey information or regional data. The system can predict base age 50-site index within 1.7 m (5.5 ft). It is presented as a stand-alone computer application, but the source code could be extracted and incorporated into larger growth and yield systems. As Shoulders and Tiarks (1980) developed their equation from data arising only from Louisiana and Mississippi, Harrington's (1990) system might be more suitable outside those two states.

Evaluating Growing Stock and Stand Density of Longleaf Pine Stands

Stand density affects growth and shape of individual trees as well as understory plant communities and affects habitat quality for wildlife (Grelen and Lohrey 1978; Clutter et al. 1983; Haywood et al. 1998). Stand density can be described as simple measurements of number of trees, basal area, or volume per acre. Or the variables may be combined into a stand density index. Most stand density indices are functions of two or more of (1) basal area per acre, (2) trees per acre, or (3) average tree size (in terms of quadratic mean diameter, volume, or weight). Most stand density indices are independent of stand age and site quality, except as those variables influence tree size and mortality. Reineke's (1933) stand density index (SDI) is $N(10/D_q)^{-1.605}$, where N represents number of trees per acre, D_q represents quadratic mean diameter, and −1.605 is an empirically derived constant for all species. The Reineke relationship arose out of the observation that there seemed to be a limiting straight-line relationship when the logarithm of quadratic mean diameter was plotted versus the logarithm of trees per acre. Reineke (1933) suggested a maximum stand density index of 400 for longleaf pine, which is the same as the maximum SDI of shortleaf and slash pines, but less than the maximum for loblolly pine (450). The southern variant of the Forest Vegetation Simulator (Donnelly et al. 2001) uses a maximum Reineke stand density index of 390 for longleaf pine, based on their data.

The actual maximum density line has limited applicability to management since most forests would be maintained at densities much less than the maximum. However, a line can be defined that is parallel to the limiting density line that represents the threshold of significant density-dependent mortality (Drew and Flewelling 1979; Dean and Baldwin 1993). This line typically represents 50% to 55% of the maximum density. Under typical management, a stand would be maintained at or below this level of density.

In Fig. 2, we plot a limiting relationship for longleaf pine plantations from a large database

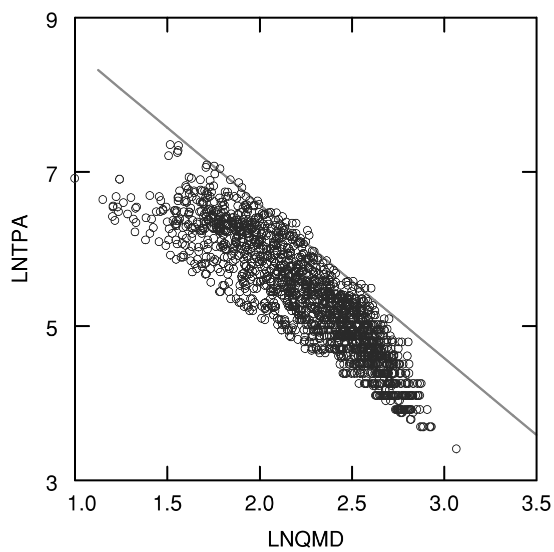


FIGURE 2. A limiting density relationship for longleaf pine plantations. Only plots with a Reineke stand density index of 100 or greater were used. The line was fit by minimizing the function: $loss = (observed - predicted)^2 \left(N\left(\frac{D_q}{10}\right)^{-1.992}\right)^{12}$. This weighting ensures that the line will approach the limit of the data. Note that there are no plots with large quadratic mean diameter near the limiting line; plots with the largest quadratic mean diameter were thinned fairly heavily.

(Goelz and Leduc 2001). However, we found the exponent to be −1.992, rather than Reineke's −1.605. If the exponent was −2, this would indicate that the limiting density relationship would represent a maximum basal area for all levels of quadratic mean diameter. As −1.992 is very close to −2, the maximum basal area is 49.1 m^2/ha ± 0.19 (214 ft^2/acre±2) across a wide range of quadratic mean diameter from 6.4 to 66 cm (2.5 to 26 in.). The southern variant of the Forest Vegetation Simulator (FVS) employs a maximum basal area of 48.9 m^2/ha (213 ft^2/acre) (Donnelly et al. 2001). This is very similar to the maximum indicated by the data of Goelz and Leduc (2001). However, this should not be surprising, as Donnelly et al. (2001) incorporated the data of Goelz and Leduc (2001) with data they had available from natural stands.

We used the limiting density relationship to build a density management diagram for longleaf pine plantations. As the exponent is not −1.605, we call the index the Goelz–Leduc stand density index (GLSDI) for longleaf pine, rather than the Reineke stand density index. It may be calculated as $N(D_q/10)^{-1.992}$, with the maximum SDI calculated to be approximately 393. Three lines are present on Fig. 3. There is a maximum density line, a line representing 50% of maximum, or the threshold for significant density-dependent mortality, and a line that represents crown closure, as determined by the equations of Smith et al. (1992) for crown diameter of open-grown longleaf pine. As the GLSDI is based on an exponent very close to two, and as Smith et al. (1992) predict open-grown crown diameter as a linear function of diameter, basal area is nearly constant across a broad range of diameter. Thus, maximum basal area is approximately 44.7 m^2/ha (215 ft^2/acre), the threshold for significant density-dependent mortality is 22.2 m^2/ha (107 ft^2/acre), and crown closure occurs at approximately 14.5 m^2/ha (63 ft^2/acre). Appropriate levels of basal area would vary depending on management objectives. However, a basal area of 14.5 m^2/ha (63 ft^2/acre) would provide high rates of individual tree growth while not sacrificing much whole stand growth. Higher levels of basal area would produce slower individual tree growth, but somewhat greater whole stand growth, somewhat higher log quality, and losses to mortality would be slight if stands were thinned before they exceeded 24.6 m^2/ha (107 ft^2/acre). Although the data of Goelz and Leduc (2001) included some plots with greater than 49.4 m^2/ha (215 ft^2/acre) of basal area, the plots were small (roughly 0.04 ha, 0.1 acre) and were not likely indicative of larger plots (0.4 ha, 1.0 acre) or stands.

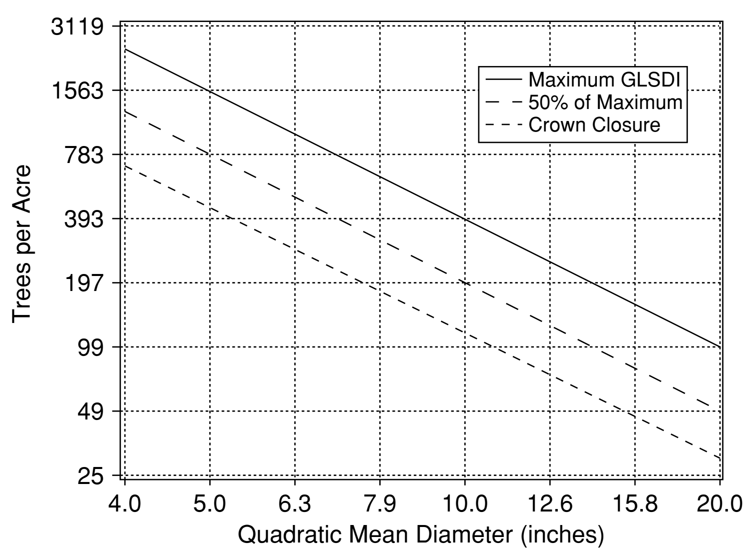


FIGURE 3. Density management diagram for longleaf pine plantations. Lines are drawn for maximum density, 50% of maximum, and for crown closure. Note the axes are scaled logarithmically.

The GLSDI also can be used to help guide initial planting density. We will consider two thresholds for thinning—50% of maximum GLSDI and 4/3 times the density at crown closure. The former threshold implies removal of one-third to one-half of the basal area while the latter implies removal of about one-fourth to one-third of the basal area in the thinning. Merchantability of a thinning will be influenced by size of the trees that are harvested. We consider first thinnings at quadratic mean diameters between 10.2 and 30.5 cm (4 and 12 in.). We explore three levels of survival to first thinning—50%, 70%, and 90%. Note this is survival to first thinning, not initial survival. Finally, our calculations assume there are no desirable volunteer trees in the plantation. If quadratic mean diameter is 10.2 cm (4 in.), and survival to first thinning is 90%, 3033 trees/ha (1355 trees/acre) must be planted to produce 24.6 m^2/ha (107 ft^2/acre). At a quadratic mean diameter of 15.2 cm (6 in.), 1492 trees/ha (604 trees/acre) are required, and at 20.3 cm (8 in.), 138 surviving trees/ha (341 trees/acre) are needed. So, if thinning a stand with a quadratic mean diameter of 15.2 cm (6 in.) is practicable, and the manager sought to maximize total volume growth, initial planting density should be about 1483/ha (600/acre), assuming survival of 90%. If survival were 70%, more than 1903 trees/ha (770 trees/acre) would be planted. The consequence of lower than expected survival means that thinning could be delayed a few years until quadratic mean diameter is greater. For example, if 90% survival were anticipated, but 50% was achieved, thinning would be delayed until quadratic mean diameter was at least 5.1 cm (2 in.) larger than anticipated, which is predicted to be about 5 years later using the model of Lohrey and Bailey (1977). Besides the delay to first thinning, there would likely be a reduction in log quality. A stand that is not sufficiently dense to thin until it has a quadratic mean diameter from 25.4 to 20.5 cm (10 to 12 in.) will likely have more defects due to knots and persistent dead branches, unless pruning was performed.

Acknowledgments

Drs. Tom Croker and William Boyer are acknowledged for the work they did over the decades at the Escambia Experimental Forest and for their teachings on how to naturally regenerate longleaf pine and manage it. We extend our sincere thanks to Dr. Robert M. Farrar, Jr. It was his tenacity that has provided much of the data available today for modeling longleaf pine growth and yield.

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