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Using a Density-Management Diagram to Develop Thinning Schedules for Loblolly Pine Plantations

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SUMMARY

A method for developing thinning schedules using a density-management diagram is presented. A density-management diagram is a form of stocking chart based on patterns of natural stand development. The diagram allows rotation diameter and the upper and lower limits of growing stock to be easily transformed into before and after thinning densities. Site height lines on the diagram together with site index curves then allow the timing of thinnings to be specified. Intermediate and final harvest volumes are calculated with a growth and yield simulator capable of recovering the diameter distribution within the plantation. The development of thinning schedules by this method is illustrated for loblolly pine *(Pinus taeda* L.) plantations.

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INTRODUCTION

Thinnings can increase total stand yield by utilizing merchantable trees that would otherwise die and by maintaining rapid growth of individual trees by minimizing competition. Thinnings must be timed correctly, however, if benefits are to be maximized. Growing stock is liquidated and total stand yield is reduced when stands are thinned too early, the trees respond slowly, if ever, when stands are thinned too late. Although field trials are undoubtedly the best way to determine the proper timing of thinnings, they have serious limitations. They take many years to complete, and their results cannot be applied accurately where site quality and management objectives differ from those encountered in the trials. A more theoretical approach, one that makes use of a density-management diagram has been introduced (Drew and Flewelling 1979). This method allows foresters to develop thinning schedules quickly for a wide range of site qualities and management objectives. The concepts behind density-management diagrams are explained, and the use of such a diagram in the development of thinning schedules for loblolly pine *(Pinus taeda* L.) plantations are demonstrated here.

BASIC CONCEPTS

A density-management diagram is a stocking chart based on natural stand development expressed as changes in average tree size and trees per acre over time. After a natural disturbance or regeneration cut, trees become established and grow until further growth requires more resources than the site can supply. After this point, growth can occur only if resources are released through mortality. Increased average stem mass, volume, or diameter and the associated reduced numbers of trees per acre during this period of mortality form a boundary relationship that closely approximates a negatively sloped line when the data are plotted on logarithmically scaled axes (fig. 1). This boundary forms the outline of the density-management diagram. Since the boundary is largely independent of tree age and site quality (Reineke 1933), a density-management diagram is applicable to a wide range of conditions.

Several sets of lines are usually included in the diagram so that users can determine stand density, average height of dominants and codominants, and one other size parameter. Several measures of stand density are based on the tree size-tree number boundary. Such measures include relative density (Drew and Flewelling 1979) and stand density index

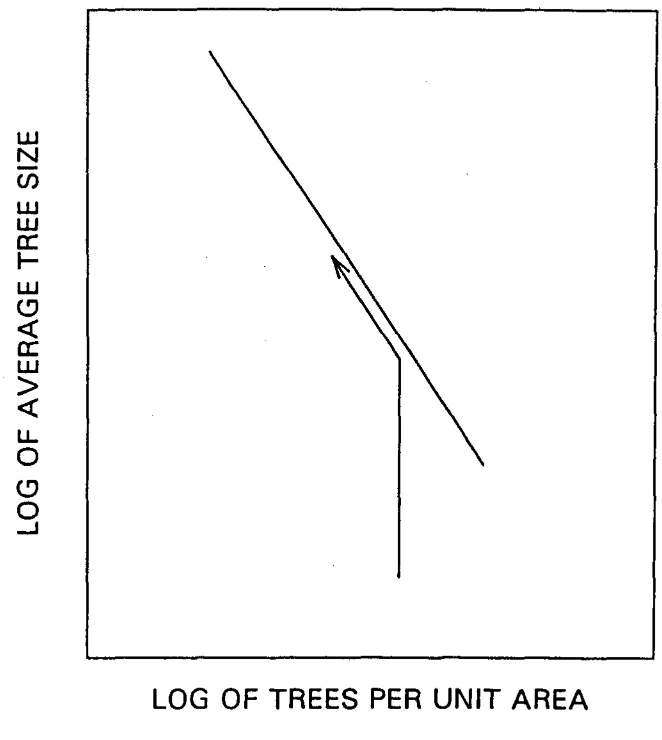

Figure 1. — *Ideal boundary relationship between the log of average tree size and the log of trees per unit area. The arrow traces the development of an ideal even-aged stand.*

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(Reineke 1933). Lines representing constant values of such density measures are parallel to the tree size-tree number boundary.

Together with site index curves, the lines representing the average height of dominants and codominants (site height) allow stand age to be determined for any combination of tree size and tree number. Stand age is found by simply locating the site height corresponding to a particular tree size-tree number on the height-over-age curve for a given site index. Analysis of data for slash pine *(Pinus elliottii* var. *elliottii* Englem.) plantations indicate that a single set of height lines may be adequate even when fertilization regimes and soil types differ from stand to stand (Dean and Jokela 1992).

Choice of the second size variable to be overlaid on the diagram depends on the choice of the size variable for the Y-axis. The first density-management diagram introduced in the United States was based on a boundary between average stem volume and trees per hectare (Drew and Flewelling 1979). Drew and Flewelling overlaid quadratic mean diameter (D_q) on the diagram so that they could estimate basal area. Other density-management diagrams are based on the boundary between D_q and trees per acre (Dean and Jokela 1992, Long and others 1988, McCarter and Long 1986). In diagrams of the latter type, total standing volume is overlaid so that intermediate and final volume removals can be estimated.

LOBLOLLY PINE DENSITY-MANAGEMENT DIAGRAM

The density-management diagram that will be used to illustrate the construction of thinning schedules for loblolly pine plantations is based on the diagram developed by McCarter and Long (1986). In this diagram, the Y-axis represents D_q, the X-axis represents trees per acre *(TPA),* and stand density is expressed as Reineke's stand density index *(SDI).*[1] Site height overlies the *SDI* lines.

The tree size-tree number boundary and site height lines were developed from data collected on permanent plots in unthinned loblolly pine plantations in Louisiana, southwestern Mississippi, and southeastern Texas. A complete description of the plantations is given in Baldwin and Feduccia (1987). According to these data, the tree size-tree number boundary for loblolly pine corresponds to an *SDI* of 450. This value agrees with the maximum *SDI* found by Reineke (1933) for loblolly pine.

[1] $SDI = TPA \cdot (D_q/10)^{1.6}$.

Following McCarter and Long (1986), two regression equations are used to plot the site height lines:

$$D_q = 8.61 \cdot V^{0.28} \cdot TPA^{-0.39}$$
(n = 271, S.E.$_{\cdot y}$ = 0.54 inches)

and

$$V = 0.001 \cdot D_q^{1.73} \cdot H^{1.36} \cdot TPA$$
(n = 271, S.E.$_{\cdot y}$ = 524 feet^3/acre)

where

V is total stem volume (feet^3/acre) and
H is site height (feet).

The regression equations were determined with one-half of the data, and their goodness of fit was determined with the remainder.

The loblolly pine density-management diagram developed from these data is shown in figure 2. Stand density is expressed as a percentage of maximum *SDI.* The ranges of D_q, site height, and trees per acre are the ranges observed in the sampled plantations (table 1). The site-height lines in the loblolly pine diagram differ substantially from those in diagrams for lodgepole pine *(Pinus contorta* var. *latifolia* Engelm.) (McCarter and Long 1986) and slash pine (Dean and Jokela 1992). In lodgepole and slash pines, only extremely high densities significantly affect the relationship between height and diameter. In loblolly pine, however, the diameter associated with a particular height diminishes rapidly with increasing stand density.

THINNING SCHEDULES

Basic Parameters

Within the framework of the density-management diagram, three factors determine the schedule of thinnings: (1) the target diameter at rotation, (2) the

Table 1— *Mensurational statistics for the loblolly pine plantations used to construct the density-management diagram*

Variable	Mean*	S.D.	Minimum	Maximum
D_q†	7.7	2.0	3.4	15.1
TPA‡	462	225	48	1,230
H_s§	54.2	13.6	17.4	89.7
V¶	3,360	1,660	60	8,390
SI**	61	8	37	89

*n = 542.
†Quadratic mean diameter (inches).
‡Trees per acre.
§Site height (feet).
¶Total stem volume (feet^3/acre).
**Site index (H_s at age 25).

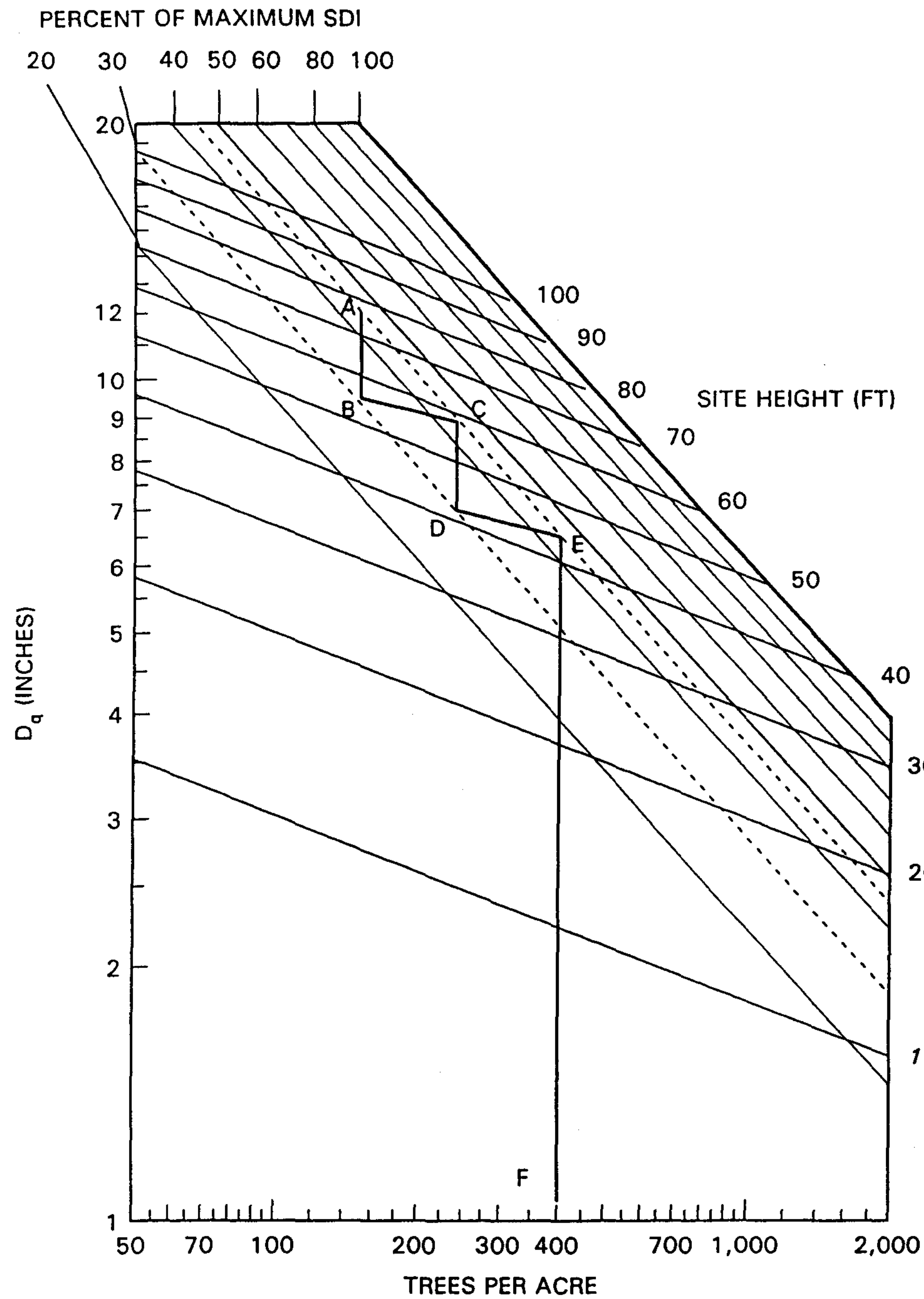

Figure 2. — *Thinning sequence for a hypothetical stand plotted on the loblolly pine density-management diagram. Dotted lines denote upper and lower growing stock limits for this example.*

upper growing-stock limit, and (3) the lower growing-stock limit. Whereas these criteria are usually determined by timber objectives, they can also be set according to any nontimber objective that can be expressed in terms of tree size and trees per acre.

The objectives in establishing the upper limit of growing stock are avoiding density-related mortality and maintaining live-crown ratios above 40 percent, the recommended minimum for good tree vigor (Smith 1986). Figure 1 depicts mortality in an idealized stand. In reality, density-related mortality is episodic and irregular and causes a stand to move toward and away from the tree size-tree number boundary at unpredictable intervals. Also, density-related mortality does not always begin near the size-tree number boundary. It can begin at about 50 to 55 percent of maximum density (Dean and Jokela 1992, Drew and Flewelling 1979). Density-related mortality for these loblolly pine plantations began at about 50 percent of maximum *SDI* (fig. 3). Curiously, the relative density

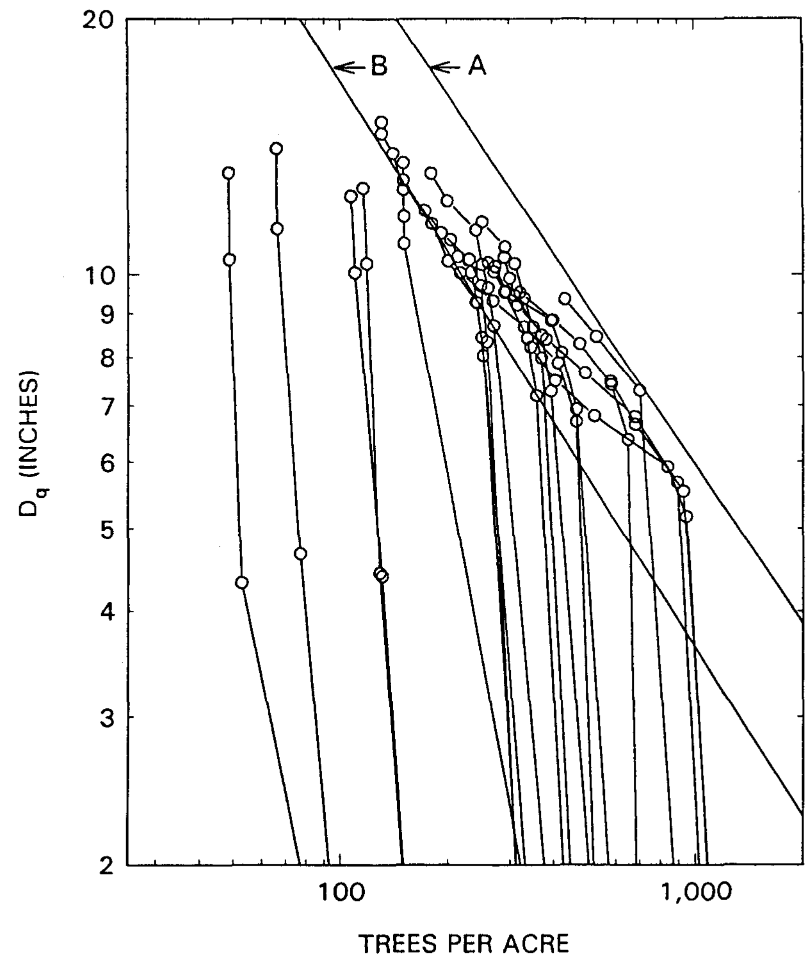

Figure 3. — *Trajectories of the quadratic mean diameter* (D_q) *and trees per acre for remeasured loblolly pine plantations. Lines labeled A and B are the tree size-tree number boundary and the threshold of the density-related mortality, respectively.*

associated with the beginning of density-related mortality is about the same relative density associated with a 40-percent live-crown ratio (Long 1985).

In practice, the upper growing stock limit for a particular stand may be set lower than the threshold of density-related mortality for any of several reasons. Because increased stand yield is obtained at the expense of diameter, growing stock may be kept low so that diameter objectives can be achieved quickly. Also, thinnings cannot always be conducted in the exact year for which they are planned. If stands at the threshold of density-related mortality cannot be thinned on schedule, live-crown ratios will fall below 40 percent, and average tree vigor will be severely reduced. In addition, the management objective may require that some growing space be allocated to understory vegetation or that some resources, such as water, pass through the stand. In our example (fig. 2), the upper growing stock limit will be set at 45 percent of maximum *SDI*.

The principal objective in setting the lower growing stock limit is to maintain adequate site occupancy. The lower limit is usually set somewhat above canopy closure because canopy closure marks the beginning of competition for resources. The recommended lower stocking limit for several western coniferous species is 35 percent of maximum SDI (Long 1985). This value, however, cannot be applied to loblolly pine. The potential thinning yield is defined by the distance between the upper and lower growing stock limits. Because the maximum *SDI* for loblolly pine is substantially lower than that for many of the western conifers, thinnings that would keep stand density between 35 and 45 percent of maximum *SDI* might not be operational. For loblolly pine, canopy closure occurs at about 25 percent of maximum density (data from Smith and others 1992). This suggests that the lower growing stock limit can be set at 30 percent of maximum density, which will improve the economics of thinnings in loblolly pine plantations without sacrificing full occupancy of the site.

Scheduling

The thinning schedule can be developed once the rotation diameter and the upper and lower limits of growing stock have been set. This is best illustrated by example. Assume that the target harvest diameter is 12 inches and that the upper and lower growing stock limits are set at 45 and 30 percent of maximum *SDI*, respectively. Furthermore, assume that D_q must be greater than 5 inches and that thinnings must yield at least 4 cords/acre in order to be operational.

The procedure for scheduling thinnings is as follows. In this example, the point at which the 12 inches D_q line intersects the 45-percent *SDI* line (fig. 2, point A) represents stand conditions at final harvest. The sequence of thinnings to reach this point is found by stair-stepping backward between the upper and lower growing stock limits until D_q drops below 5 inches.

The sloped and vertical segments of the stair-steps represent the thinning and post-thinning phases, respectively (fig. 2). The post-thinning growth segments (AB and CD) are drawn on the assumption that there is no mortality between thinning intervals. Although density-independent mortality may occur at any time from lightening strikes, wind blows, ice damage, etc., it is assumed for planning purposes that no trees are lost between thinnings as long as stand density remains below 50 percent of maximum *SDI*. The thinning segments (BC and DE) are sloped slightly to represent the effect of thinning on size distribution. In this example, thinnings are from below. Normally, to account for the increase in D_q with low thinning, these segments are drawn parallel with the nearest site height line on the assumption that low thinning has no effect on site height. However, since the site height lines for these loblolly pine plantations plot linear on the diagram in contrast to curvilinear as in other diagrams (Dean and Jokela 1992, Drew and Flewelling 1979, McCarter and Long 1986), keeping the thinning segments parallel with the nearest height line may not be suitable for loblolly pine plantations. Analysis with COMPUTE_P-LOB, a growth and yield simulator for loblolly pine (Ferguson and Baldwin 1987), suggests that low thinning increases the value of D_q by a factor of about 1.07; therefore, the thinning segments are drawn so that the ratio between the residual and before-thinning values of D_q equals 1.07 (table 2).

One determines when to thin and harvest the plantation by referring to the site height lines and height-age curves (fig. 4). All cutting operations occur when the plantation is at 45 percent of maximum *SDI* (fig. 2, A, C, and E). Site heights at these points are 44, 58, and 78 feet in the present example. If the site index were 60 feet at age 25, the plantation would be thinned at 15 and 24 years and then harvested at 41 years (table 2). If the site index were 70 feet, the stand would be thinned at ages 12 and 18 and harvested at age 30.

Determining Yields

Volume lines on a density-management diagram are useful in understanding the basic structural interrelationships within the stands and how these relationships vary with density. They have little value as predictors of merchantable yields from loblolly pine plantations, however, because top diameters change with product specification. Merchantable yields must be determined with a growth and yield simulator such as COMPUTE_P-LOB (or PLOB for short) (Baldwin and Feduccia 1987, Ferguson and Baldwin 1987); PLOB calculates stem volume by 1-inch diameter classes for three user-specified top diameters, and it also calculates board-foot volume for trees with a d.b.h. greater than 10 inches.

If one uses PLOB to calculate thinning yields, one must bypass PLOB's survival functions; PLOB's equa-

Table 2.— *Mensurational data for the example thinning sequence shown in figure 2*

Operation	Trees/acre		D_q*		BA†		H_s‡	Age§ (60/70)	Yield¶
	Before	After	Before	After	Before	After			
Planting	400								
Thinning	400	241	6.5	7.0	92	64	44	15/12	6.6 cords
Thinning	240	150	8.9	9.5	104	74	58	24/18	7.9 cords
Harvest	150		12.0		118		78	41/30	8.2 MBF

*Quadratic mean diameter (inches).
†Basal area (feet^2/acre).
‡Site height (feet).
§Age (years) at site indexes 60 and 70 (base age 25).
¶Per acre.

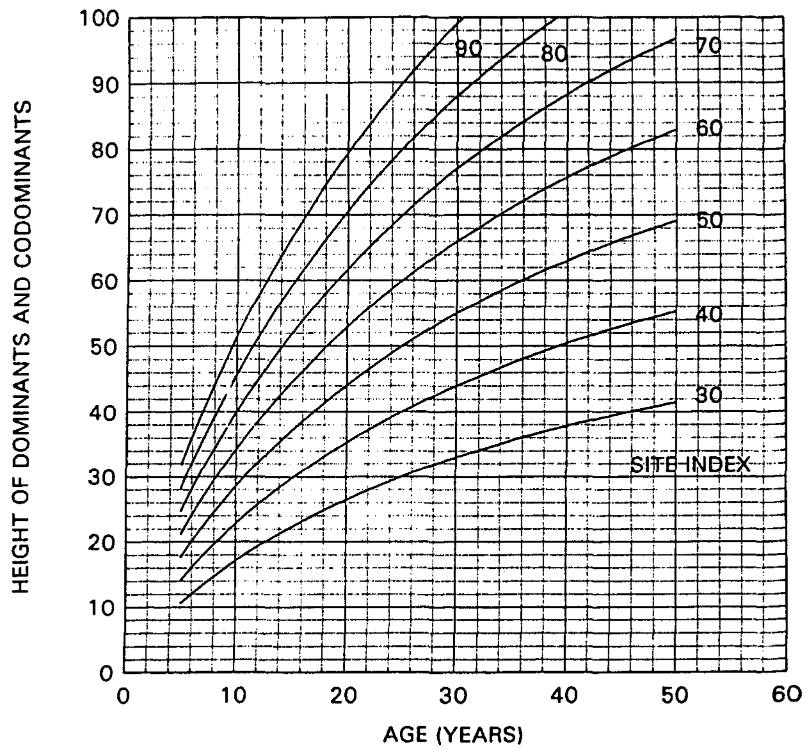

Figure 4. — *Height and age by site index (base age 25). Curves are from an equation from Baldwin and Feduccia (1987).*

tions predict survival at any stage of stand development as functions of each stand variables as age, basal area, mean dominant height, or site index. The predictions generated are inconsistent with the procedural assumption required by this technique that no mortality occurs below 50 percent of maximum *SDI*. Survival functions of PLOB are bypassed by not allowing the program to project stand condition through time. Stand conditions just before thinning or harvest are entered in the program. Yields are then calculated by specifying a residual basal area (calculated from diagram values of after-thinning D_q and number of trees per acre) or a complete harvest. In this example, PLOB would be run three times to obtain yields from the two thinnings and the final harvest. The simulator predicted that the first thinning would yield 6.6 cords/acre of pulpwood,[2] that the second thinning would yield 7.9 cords/acre of chip-and-saw material,[3] and that the final harvest would yield 8.2 MBF/acre of sawtimber[4] (table 2).

CONCLUSIONS

The approach outlined here for developing thinning schedules for loblolly pine plantations is adaptable to a wide range of situations. Any combination of harvest diameter and upper and lower growing stock limits can be accommodated across a wide range of site qualities. Because merchantable volumes can be calculated with a growth and yield simulator, it is relatively easy to develop alternative thinning schedules and to compare these alternatives using economic criteria. Also, as more information becomes available concerning structural habitat requirements of wildlife species or structural requirements to produce nontimber resources, this information can be overlaid on the density-management diagram. For example, structural requirements of elk hiding cover has been overlaid on the lodgepole pine density-management diagram (Smith and Long 1987).

[2]D.b.h. >4.5 inches to a 4-inch top.
[3]D.b.h. >7.5 inches to a 6-inch top.
[4]D.b.h. >9.5 inches to a 8-inch top.

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A density-management diagram for loblolly pine plantations in the West Gulf region of the Southern United States and its usage in developing thinning schedules are presented.

Keywords: mortality, *Pinus taeda* L., planting density, Reineke's stand density index.

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