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Stockability: A Major Factor in Productivity Differences Between Pinus taeda *Plantations in Hawaii and the Southeastern United States*

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ABSTRACT. Basal area and volume production in loblolly pine spacing trials in Hawaii were nearly double the average production in research plantings in the Southeastern United States. The higher productivity in Hawaii was associated, to some extent, with site index and more rapid growth of individual trees. Competition-related mortality, however, was considerably lower in Hawaii, despite the fact that trees were larger. Consequently, limiting density and mortality threshold boundary lines were much higher. Such differences in stockability (or maximum mean tree size-stand density relationships) accounted for most of the differences in productivity. Forest managers and scientists should pay more attention to possible differences in stockability in the quest for productivity improvement. FOR. SCI. 35(3):708–719.

ADDITIONAL KEY WORDS. Stocking, self-thinning, loblolly pine, spacing, yield.

PRELIMINARY OBSERVATIONS of a loblolly pine (*Pinus taeda* L.) spacing trial in Hawaii indicated that stand growth was exceptionally high and suggested that tree size-stand density relationships might be markedly different from those in the Southeastern United States. Subsequent assessment of stand characteristics in the Hawaii trial and comparison with data from research plantings in the Southeast confirmed these observations. In this paper, we evaluate stand characteristics associated with productivity differences among plantations in the two locations, and discuss the implications of our findings.

Productivity of a stand is a function of tree growth rate and number of trees per unit area. Much of the current technology in North American timber management has been influenced by two assumptions: (1) opportunities to affect tree growth rate are abundant for many species, and (2) opportunities to increase the number of trees per unit area that can be grown to a given size are limited. The latter assumption is commonly stated in terms of "constant slope and level" of self-thinning trajectories (e.g., Drew and Flewelling 1977, 1979) or limiting diameter-density lines (e.g., Reineke 1933, Reukema and Bruce 1977) for individual species. These considerations are reflected in many stocking (thinning) guidelines and yield tables. In

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addition, silvicultural and genetic efforts to improve productivity have generally focused on enhancing tree growth rate, and, to some extent, on increasing harvest index (usable proportion of total biomass) and product quality. Considerably less effort has been spent on examining productivity differences in terms of numbers of trees that can be grown to a given size per unit area or on attempts to improve productivity by increasing such numbers.

We will use the term "stockability" to refer to such differences in *maximum* mean tree size-density relationships. In a conceptual sense, stockability can be regarded as the tolerance of a forest system to the presence of and/or competition from increasing numbers of trees. This tolerance may differ with environment and, in that regard, might be considered an aspect of site quality *independent* of that reflected in site index or potential height growth (cf. Sterba 1987). It may also differ with genotype and stand cultural methods. Stockability can be assessed quantitatively by several parameters, including: (1) maximum mean size-density lines [e.g., Reineke's (1933) stand density index and the self-thinning rule (Yoda et al. 1963)]; (2) size-density combinations above which competition-related mortality begins [e.g., Reukema and Bruce's (1977) D-Max line]; and (3) size-density combinations above which growth rate of individual trees is reduced below some specified level. In physiological studies and evaluations, one might determine size-density combinations above which important processes or conditions are adversely affected in relation to some threshold or standard.

The term "stockability" has been used in a more limited sense by Hall (1983) in discussing his growth basal area concept, which in essence proposes using the basal area at which 100-year-old dominant trees grow 25 mm per decade as a measure of site limitations on stockability. Other workers have used different terms in referring to various elements of this concept—"stocking capacity" (MacLean and Bolsinger 1973), "carrying capacity" (Strub and Bredenkamp 1985, Buford 1986, Harrison and Daniels 1988, Schmidling 1988), and "potential density" (Sterba 1987). Although stockability differences *within* a site class have received little attention in the past by most North American foresters, they are inherent in the "Ertragsniveau" concept of Assmann and Franz (1963) and in the production classes of the British forest management tables (Bradley et al. 1966). In both instances, three yield levels are recognized for stands of a given top height or within a top height-site class.

METHODS

Whitesell (1970, 1974) described a loblolly pine spacing trial established in 1961 on the island of Maui, HI, that has surpassed reported growth for any plantation in the southeastern United States. The trial is a well designed and maintained study of 4 spacings (1.8, 2.4, 3.0, and 3.7 m) planted in a 4 × 4 Latin square. The plots are 0.10 ha in area, with the central 25 trees forming the measurement sample. Diameters were measured on all trees at ages 4, 7, 11, 20, and 25 years; heights were measured on all 25 trees at ages 4, 7, and 11 years, and on a 9-tree subsample at ages 20 and 25 years. For purposes of comparison, a similar trial established in 1957 in the Piedmont of South Carolina (Balmer et al. 1975, Harms and Lloyd 1981) was selected. This study was planted in a randomized block design with 4 replications using the same 4 spacings as the Hawaii trial. The plots are 0.24 ha in area, with the central 64 trees forming the measurement sample. A subsample of trees was measured for height and diameter at ages 5, 7, and 11; all trees were measured at 15, 20, and 25 years. The major differences between these research plantations are location and prevailing environmental factors. Seed origin of the planting stock in both trials is unknown.

Published reports were scanned for additional spacing trials and unthinned research plantations to establish the general level of productivity of loblolly pine. Few such studies have been recorded, but 5 were found that provided sufficiently comprehensive data to make comparisons of growth possible: one in Hawaii (Schubert and Korte 1969), three in the southern United States (Hafley et al. 1982, Shepard 1974, Williston 1985), and one in Illinois (Arnold 1978).

For broad comparisons among all sites and geographic locations, we restricted our evaluation to data from similar spacings (2.4 × 2.4 m, or its closest approximation), and ages (24–25 years), thereby eliminating these factors as sources of variation in productivity. At this age and spacing, competition-related mortality had occurred in all plantations. Moreover, this spacing approximates current planting densities in the Southeast.

To evaluate the performance of the Hawaii and South Carolina plantations, we summarized the averages of tree and stand variables for each of the four spacings at age 25. We also examined the patterns of tree growth and stand development trajectories by means of diameter-age and diameter-density plottings.

RESULTS

Stand Characteristics and Productivity (General)

Primary stand characteristics of the seven plantations are shown in Table 1. All but one of the Southeastern U.S. plantings are within the natural range of loblolly pine. The southern Illinois plantation is north of the natural range but was included because of its good performance. With age and initial spacing held constant at approximately 25 years and 2.4 × 2.4 m, the major known differences among the plantations were site index and geographic location. We made no attempt to assess the influence of genotype, climate, local weather patterns, pests, pathogens, or soil characteristics on productivity differences.

Average site index (base age 25 years) was 21.2 m for the Southeastern U.S. plantings and 25.5 m for the Hawaii plantings. Among the Southeastern U.S. plantings, the North Mississippi plots were on exceptionally productive land; a site index of 25m for loblolly pine in the Southeastern United States is relatively rare (Williston 1985). Even so, volume and basal area production in the Mississippi plantation were much lower than in the Hawaii plantings, which averaged only slightly higher (0.5 m) in site index.

In general, the productivity (volume and basal area) differences between Southeastern U.S. and Hawaii plantations were associated with various combinations of number of trees surviving and mean dbh. The Hawaii plantings not only had higher survival on average than native plantings, they also had larger mean stand diameters.

Stand Structure (Hawaii vs. South Carolina)

Average stand and tree characteristics for the Hawaii and South Carolina spacing trials are summarized in Table 2. By age 25, significant mortality had occurred at all spacings except the two widest in Hawaii, where survival still exceeded 90%. Mortality was greatest at the closest spacings, and at all

TABLE 1. Stand characteristics of southeastern U.S. and Hawaii plantations of loblolly pine.

Plantation	Site index[1] (m)	Age (yr)	Trees planted[2]	Trees surviving	Survival (%)	Mean dbh (cm)	Mean height (m)	Basal area (m^2ha^{-1})	Total volume[3] (m^3ha^{-1})	Mean annual increment ($m^3ha^{-1}yr^{-1}$)	Reference
			..........*ha^{-1}*..........								
Southeastern U.S.											
Piedmont NC	18	24	1683	1166	69	20.6	15.5	39	215	8.6	Hafley et al. 1982
Piedmont SC	21	25	1683	1235	74	20.6	19.3	43	290	11.6	Harms and Lloyd 1981 with additional data
Northern MS	25	25	1701	1011	59	25.1	22.9	50	420	16.8	Williston 1985
Northern LA	21	25	1683	1124	67	21.3	18.9	40	275	11.0	Shepard 1974
Southern IL	21	25	1683	1366	81	20.1	18.0	43	284	11.4	Arnold 1978
Average	21.2	25	1686	1180	69.8	21.5	18.9	43.0	296.8	11.9	
Hawaii											
Maui HI	27	25	1683	1285	76	26.7	23.8	72	628	25.0	Schubert and Korte 1969 with additional data
Maui HI	24	25	1683	1463	87	27.2	19.9	85	608	24.3	Whitesell 1974 with additional data
Average	25.5	25	1683	1374	81.5	26.9	21.8	78.5	618.0	24.6	

[1] Site index at base age 25.
[2] 1683 = 2.4 m spacing; 1701 = 2.1 m × 2.7 m spacing.
[3] Stem volume inside bark, all trees, calculated from eqn (2), Clutter et al. 1984.

spacings it was greater in South Carolina than in Hawaii. Most mortality appeared to be related to natural competition.

Average stand dbh and height increased as spacing increased at both locations. Average dbh on the most widely spaced plots (3.7m) was 9.4 and 10.2 cm greater than the diameter on the most densely spaced plots (1.8m) in South Carolina and Hawaii, respectively. The difference between locations for any one spacing, however, was markedly greater than the difference between that spacing and the next wider or narrower spacing within a location. Diameters of the Hawaii planting were 6.3 to 7.1 cm larger than those of trees grown at the same spacings in South Carolina.

Average stand height increased by 1.7 to 1.9 m as spacing increased from 1.8m to 3.7m in South Carolina and Hawaii, respectively. The average difference between locations was 1.3m in favor of the Hawaii planting; this was also generally larger than differences between incremental spacing treatments at either location.

Stand Development (Hawaii vs. South Carolina)

Quadratic mean diameter is shown as a function of age, spacing, and location in Figure 1. Cumulative diameter growth was considerably greater in Hawaii than South Carolina over the 25-year life of the stand. Moreover, diameter growth for plots with trees of comparable mean size (~20 to 25 cm) at age 20 was at least as good in Hawaii as in South Carolina; thus, mean diameter growth attained in South Carolina at a spacing of 3.0 m was equalled or surpassed by similar-sized trees in Hawaii in stands planted at 1.8 to 2.4 m spacings.

As trees grow, stands advance through various stages of development, approaching a limiting mean size-density boundary along a characteristic path or trajectory. Following the onset of competition-induced mortality, the slope of the trajectory gradually becomes more nearly equal to the slope of the mean size-density boundary. Stand trajectories for the spacing trials were represented by plotting the logarithm of mean stand diameter over the logarithm of number of trees per unit area obtained from the measurements taken over time (Figure 2). The limiting density boundary lines were obtained by fitting the stand model of Lloyd and Harms (1986) separately to the

TABLE 2. Some average tree characteristics in 25-year-old loblolly pine stands planted at different spacings in Hawaii and South Carolina.[1]

	Planted spacing (m × m)[2]							
	1.8 × 1.8		2.4 × 2.4		3.0 × 3.0		3.7 × 3.7	
Characteristic	HI	SC	HI	SC	HI	SC	HI	SC
Trees per ha								
Planted	2990	2990	1683	1683	1077	1077	746	746
Surviving	2063	1611	1463	1235	1003	936	739	628
Percent	69	54	87	74	93	87	99	84
Mean dbh (cm)	24.1	17.8	27.2	20.6	30.5	23.4	34.3	27.2
Mean height (m)	19.8	18.1	19.9	19.3	20.5	19.4	21.7	19.8

[1] Each value represents an average of four replicated plot means.

[2] Plots were established using English units of measurement; the spacings stated are approximate metric equivalents. For this reason, trees per ha do not correspond to the stated metric spacing.

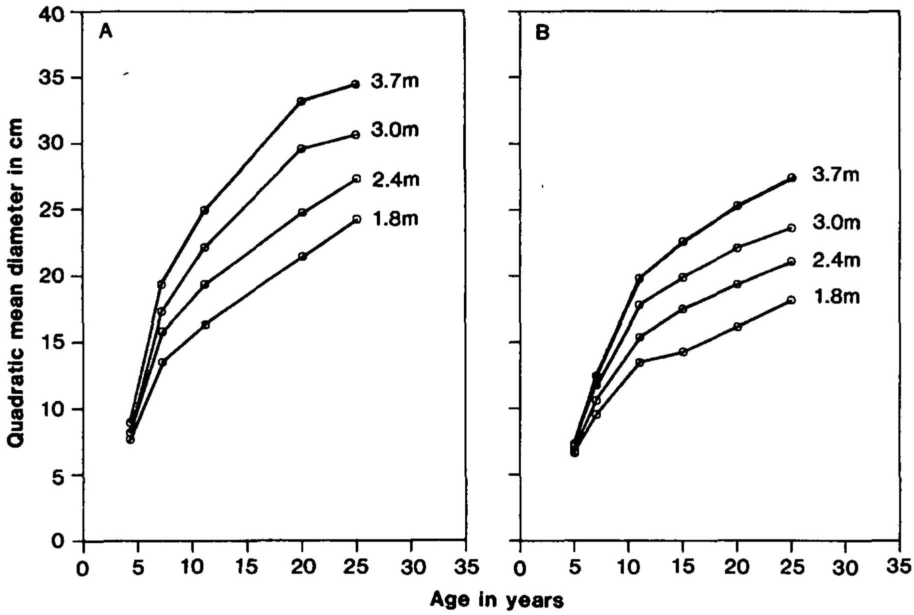

FIGURE 1. Patterns of diameter growth in loblolly pine plantations in Hawaii (A) and South Carolina (B) as related to spacing.

South Carolina and Hawaii data. The mortality threshold line was positioned at the size-density combinations where mortality first exceeded 3%. Such trajectories and boundary lines provided the framework for assessing "stockability" differences and for evaluating the relative importance of

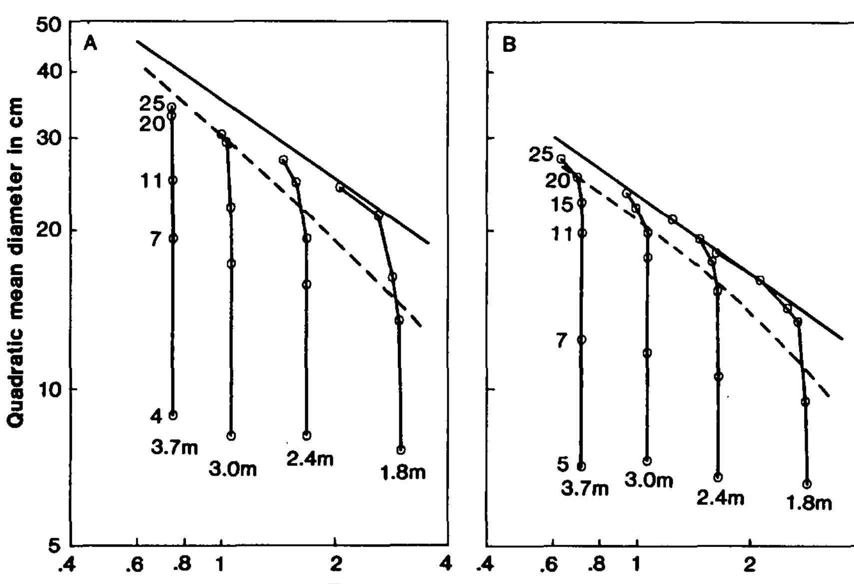

FIGURE 2. Stand development in loblolly pine plantations in Hawaii (A) and South Carolina (B): self-thinning trajectories and boundaries (limiting density—and mortality threshold- - -) plotted on logarithmic scale.

stockability and tree growth rate with regard to stand productivity in the Hawaii and South Carolina spacing trials.

The trajectories in Figure 2 exhibit the characteristic pattern of stand growth and mortality over time. Following establishment, and for a period of time that varied with spacing, the trajectories rose vertically as trees grew in size (diameter). As competition intensified and self-thinning began, the trajectories began to curve; the curvature increasing as the trajectories approached closer to the limiting size-density boundary. Thinning had progressed sufficiently in the 1.8m spacing to establish a distinct boundary at both locations. It is also apparent that the trajectories of the other spacings are tending toward the same boundaries, at the respective locations. The level of the limiting density boundary line differs markedly in the two locations; at a quadratic mean diameter of 25 cm, the Hawaii stand was estimated to contain about 1740 trees/ha whereas the South Carolina stand supports only 850 trees/ha.

The location of the mortality threshold in these stands also differs and is estimated by the broken lines in Figure 2. Mortality was first observed in South Carolina at approximately age 9 at a stand diameter of about 12 cm in the 1.8m spacing. In Hawaii, the first mortality was observed at the same spacing at about the same age, but the average diameter was about 15 cm. In this dense spacing, mortality also accelerated earlier and at smaller tree sizes in South Carolina (11 years and 14 cm) than in Hawaii (20 years and 21 cm). Mortality began in the wider spacings at progressively older ages and larger mean diameters at both locations. By age 25, all spacings but the 3.7m in Hawaii were self-thinning.

DISCUSSION

Productivity—as indicated by volume and basal area at age 25—of loblolly pine plantations in Hawaii was about double the average productivity of plantations in the Southeastern United States (Table 1). This doubling of production was associated with increased height (15%), diameter (25%), and number of surviving trees (16%) in the Hawaii plantings as compared with averages for Southeastern U.S. plantings. Trees in the highly productive Mississippi planting grew similarly to those in Hawaii, but mortality was substantially greater. Consequently, even though site index was essentially the same (~25m), stand productivity was 46% greater in Hawaii.

Productivity and other stand characteristics of the South Carolina planting are typical of the average Southeastern U.S. planting (Table 1). The comparisons of several spacing treatments in Hawaii and South Carolina show that stem growth was much more rapid in Hawaii (Table 2, Figure 1) and imply that the Hawaii and South Carolina plantings have different stockabilities. The plottings of stand trajectories clearly establish the magnitude of such differences as illustrated by markedly different levels for the mortality threshold and limiting density boundaries.

Comparison of tree numbers and sizes in the 2.4 m spacing illustrates the relative importance of the stockability and tree growth rate with regard to differences in productivity between the two plantations. At age 25, volumes were 290 and 608 m^3 ha^{-1}, respectively, in South Carolina and Hawaii. Corresponding mean diameters were 20.6 and 27.2 cm, and stocking levels were 1235 and 1463 trees/ha. If stockability, as measured by the level of the limiting density line, of the Hawaiian planting was similar to that of the South Carolina planting, no more than about 740 trees/ha of that size (27.2 cm) would have survived, and stand volume would be only about 308 m^3

ha^{-1}. Thus, very little—only about 18 m^3 ha^{-1} or about 6%—of the differences in volumes of those stands at age 25 can be attributed to differences in growth rate per se. Because the limiting density boundaries differed markedly, nearly twice as many stems of 27.2 cm diameter could be sustained in the Hawaiian planting. This difference in number of trees provides 300 m^3 ha^{-1} (or about 94%) of the 318 m^3 ha^{-1} difference in stand yield.

Although the above comparison may represent an extreme case, there is no doubt that differences in stockability exist and that they have significant impacts on stand productivity. The proportion of increased productivity that might be "allocated" either to tree growth rate or to stockability will obviously vary with stage of stand development. Differences in productivity occurring prior to the onset of competition-related mortality in the South Carolina stand would be associated primarily with differences in growth rate; as self-thinning progressed in both stands, an increasing proportion of the productivity differences would be associated with stockability differences.

What do the differences in stockability and growth rate observed between Hawaii and South Carolina plantations mean in practical terms? To evaluate such effects, we estimated the maximum number of trees that could be grown to various target mean diameters *prior* to the onset of self-thinning; i.e. at the mortality threshold (dashed line in Figure 2). We also estimated the age (from data shown in Figure 1) and average tree height (based on site index) when plantations of such densities would attain the target diameters. Mean tree volume was then estimated from height and diameter, and expanded to per ha yield based on stand stocking. We were thereby able to *approximate* mean annual production for the hypothetical stands designed to match the stockabilities observed at the two locations (Table 3). Our calculations suggest that rotation ages to attain the target diameters at the mortality threshold densities are somewhat lower in Hawaii than South Carolina. These age differences coupled with site index differences result in different heights and tree volumes at the target diameters. The difference in mean tree volume varies from 4 to 10% in favor of the South Carolina planting, but the difference in target densities produces estimated total yields that are 40% to 80% greater in Hawaii. On a per annum basis, the hypothetical Hawaii plantations will produce 86 to 102% more than the hypothetical South Carolina plantings. It therefore appears that differences in yields between plantations "tailored" to the differing stockabilities of the stands in these two locations are substantial and considerably greater than would be expected from differences in site index alone.

IMPLICATIONS

Given that high stockability plays a significant role in the exceptional productivity of loblolly pine plantations in Hawaii, what is the likelihood that stockability differences exist and may significantly affect productivity of loblolly pine and other species in their native habitat? Much earlier and current literature postulates that stockability is relatively constant for tree species; that is, the slope and intercept of the limiting density boundary do not differ within a species over a wide range of ages, environments, and management conditions (Reineke 1933, Daniel et al. 1979, Westoby 1984, Long 1985). Accordingly, for any given species, genetic and cultural manipulations are presumed by some workers to affect the time required for a tree crop to attain some "fixed" limiting density, but not increase its level. Such views are supported by several studies, most of which were done with

TABLE 3. Characteristics of hypothetical plantations designed to match stockabilities observed in South Carolina and Hawaii.

Target diameter (cm)	Stand density		Rotation age		Estimated height		Mean tree volume		Estimated yield		Mean annual productivity	
	SC	HI	SC	HI	SC	HI	SC	HI	SC	HI	SC	HI
	(tph)		(yr)		(m)		(m^3)		($m^3 ha^{-1}$)		($m^3 ha^{-1} yr^{-1}$)	
15	1,850	2,850	12	9	12.3	11.3	0.0776	0.0705	144	201	12.0	22.3
20	1,100	1,900	15	13	14.7	14.2	0.1643	0.1580	181	300	12.1	23.1
25	710	1,350	19	17	16.8	16.0	0.2925	0.2770	208	374	10.9	22.0

annual plants or, if done with woody perennials, were of short duration and in nursery or nursery-like environments (Wearstler 1979, Smith and Hann 1984). Also, one-time measurements of tree size and density in natural forest stands support a generally uniform slope (Reineke 1933); although a wide band of observations exists along the slope and conceivably could represent different intercepts (or levels of stockability), foresters in the United States have not found any consistent bases for characterizing or classifying different levels of the diameter-density lines.

As data from periodic long-term measurements of well-designed, replicated experiments accumulate, however, the notion of constant stockability for a species is being questioned. Recent studies in loblolly pine suggest that what we have termed stockability varies with site class in South Africa (Strub and Bredenkamp 1985) and some of the newer growth and yield models (Hafley et al. 1982, Harrison and Daniels 1987) contain self-thinning assumptions that vary with site index. Other work has shown differences among seed sources in the southeastern United States (Buford 1986, Schmidtling 1987). In contrast to our own study, the above investigations involved stands within a limited geographic area and growing under similar climatic conditions. Other bits of evidence suggest that stockability differences are not unique to loblolly pine; i.e., basal area and productivity of Douglas-fir plantations in New Zealand (Spurr 1963) appear much higher than those measured in the Pacific Northwest. Spacing studies of Douglas-fir within the Pacific Northwest also suggest differences in stockabilities with location (cf. Reukema 1979, Reukema and Smith 1987). Moreover, yield tables for conifers developed in Britain and other European countries recognize differences within species and *within* top height or site classes in stockability levels (Assmann and Franz 1963, Bradley et al. 1966). Finally, the $-3/2$ power rule of self-thinning itself has been re-evaluated and its generality questioned (Weller 1987, Zeide 1985, 1987). Zeide (1985) has suggested that differences in slope may be a useful variable for assessing biological differences in response to competition among and within species. Given the difficulties of obtaining accurate estimates of slopes and the large differences in intercepts, we believe that differences in the intercept are even more important and useful for such purposes.

We suggest that forest managers and scientists pay more attention to stockability differences in the quest for improvements in stand productivity. Specifically, we suggest that geneticists and silviculturists assess and attempt to quantify stockability in trials designed to evaluate progeny, cultural treatments, and/or environments. The area potentially available (APA), an index of growing space, has been used recently in the southeastern United States for evaluating genotypic differences in response to competition (Land and Nance 1987) and could be similarly used for examining differences associated with cultural treatments or other contrasting environments. Forest biologists also need to identify the morphological and physiological traits associated with high levels of stockability, wherever it is found, and determine how genetic, environmental, and management factors influence those traits. Such knowledge might lead to significant gains in productivity of species in their native range as well as indicate habitats where species may thrive as exotic plantings.

LITERATURE CITED

ARNOLD, L. E. 1978. Gross yield of roughwood products from a 25-year-old loblolly and shortleaf pine spacing study. For Res. Rep. No. 78-7. Agric. Exp. Stn. Univ. of Illinois at Urbana-Champaign. 4 p.

ASSMANN, E., and F. FRANZ. 1963. Vorlaufige Fichten-Ertragstafel fur Bayern. Institut fur Ertragskunde der Forstlichen Forschungsanstalt Munchen. 113 p.

BALMER, W. E., E. G. OWENS, and J. R. JORGENSEN. 1975. Effects of various spacings on loblolly pine growth 15 years after planting. USDA For. Serv. Res. Note SE-211. 7p.

BRADLEY, R. T., J. M. CHRISTIE, and D. R. JOHNSTON. 1966. Forest management tables. For. Comm. Bookl. No. 16. London. 218 p.

Buford, M. A. 1989. Mean stem size and total volume development of various loblolly pine seed sources planted at one location. Can. J. For. Res. (in press).

CLUTTER, J. L., et al. 1980. Stand structure and yields of site prepared loblolly pine plantations in the lower coastal plain of the Carolinas, Georgia, and north Florida. USDA For. Serv. Gen. Tech. Rep. SE-27. 173 p.

DANIEL, T. W., J. A. HELMS, and F. S. BAKER. 1979. Principles of silviculture. McGraw-Hill, New York. 500 p.

DREW, T. J., and J. W. FLEWELLING. 1977. Some recent Japanese theories of yield-density relationships and their application to Monterey pine plantations. For. Sci. 23:517–533.

DREW, T. J., and J. W. FLEWELLING. 1979. Stand density management: An alternative approach and its application to Douglas-fir plantations. For. Sci. 25:518–532.

HAFLEY, W. L., W. D. SMITH, and M. A. BUFORD. 1982. A new yield prediction model for unthinned loblolly pine in plantations. Bioecon. Model. Proj. Tech. Rep. 1. South. For. Res. Cent. Sch. For. Res. North Carolina State Univ., Raleigh. 65 p.

HALL, F. C. 1983. Growth basal area: A field method for appraising forest site potential for stockability. Can. J. For. Res. 13:70–77.

HARMS, W. R., and F. T. LLOYD. 1981. Stand structure and yield relationships in a 20-year-old loblolly pine spacing study. South. J. Appl. For. 5:162–165.

HARRISON, W. C., and R. F. DANIELS. 1988. A new biomathematical model for growth and yield of loblolly pine plantations. *In* Forest growth modelling and prediction. USDA For. Serv. Gen. Tech. Rep. NC-120:293–304.

LAND, S. B., JR., and W. L. NANCE. 1987. APA: A useful tool for analyses of progeny tests. P. 300–311 in Proc. 19th South. For. Tree Improv. Conf. 456 p.

LLOYD, F. T., and W. R. HARMS. 1986. An individual stand growth model for mean plant size based on the rule of self-thinning. Ann. Bot. 57:681–688.

LONG, J. N. 1985. A practical approach to density management. For. Chron. 61:23–27.

MACLEAN, C. D., and C. L. BOLSINGER. 1973. Estimating productivity on sites with a low stocking capacity. USDA For. Serv. Res. Pap. PNW-152. 18 p.

REINEKE, L. H. 1933. Perfecting a stand-density index for even-aged forests. J. Agric. Res. 46:627–638.

REUKEMA, D. L. 1970. Forty-year development of Douglas-fir stands planted at various spacings. USDA For. Serv. Res. Pap. PNW-100. 21 p.

REUKEMA, D. L., and D. BRUCE. 1977. Effects of thinning on yield of Douglas-fir: Concepts and some estimates obtained by simulation. USDA For. Serv. Gen. Tech. Rep. PNW-58. 36 p.

REUKEMA, D. L., and J. H. G. SMITH. 1987. Development over 25 years of Douglas-fir, western hemlock, and western redcedar planted at various spacings on a very good site in British Columbia. USDA For. Serv. Res. Pap. PNW-RP-381. 46 p.

SCHMIDTLING, R. C. 1988. Racial variation in self-thinning trajectories in loblolly pine. P. 611–618 *in* Forest Growth Modelling. USDA For. Serv. Gen. Tech. Rep. NC-120.

SCHUBERT, T. H., and K. H. KORTE. 1969. Early growth and development of four pine species in Hawaii. USDA For. Serv. Res. Note PSW-189. 4 p.

SHEPARD, R. K., JR. 1974. An initial spacing study. P. 121–128 in Southern and Southeastern For. Exp. Stn. (eds.). Proc. Symp. on Management of Young Pines. 349 p.

SMITH, N. J., and D. W. HANN. 1984. A new analytical model based on the −3/2 power rule of self-thinning. Can. J. For. Res. 14:605–609.

SPURR, S. H. 1963. Growth of Douglas-fir in New Zealand. New Zealand For. Serv. For. Res. Inst. Tech. Pap. No. 43. 54 p.

Sterba, H. 1987. Estimating potential density from thinning experiments and inventory data. For. Sci. 33:1022–1034.

Strub, M. R., and B. V. Bredenkamp. 1985. Carrying capacity and thinning response of *Pinus taeda* in the CCT experiments. S. African J. For. 128:6–11.

Wearstler, K. A., Jr. 1979. Competition-density effects and genetic improvement of yield components in loblolly pine (*Pinus taeda* L.). Ph.D. thesis, North Carolina State Univ., Raleigh. 64 p.

Weller, D. E. 1987. A reevaluation of the −3/2 power rule of plant self-thinning. Ecol. Monogr. 57:23–43.

Westoby, M. 1984. The self-thinning rule. Adv. Ecol. Res. 14:167–225.

Whitesell, C. D. 1970. Early effects of spacing on loblolly pine in Hawaii. USDA For. Serv. Res. Note PSW-223. 3 p.

Whitesell, C. D. 1974. Effects of spacing on loblolly pine in Hawaii after 11 years. USDA For. Serv. Res. Note PSW-295. 4 p.

Williston, H. L. 1985. Growth and yield of planted loblolly and shortleaf pines in a north Mississippi creek bottom. South. J. Appl. For. 9:247–249.

Yoda, K., et al. 1963. Self-thinning in overcrowded pure stands under cultivated and natural conditions. J. Biol. Osaka City Univ. 14:107–129.

Zeide, B. 1985. Tolerance and self-tolerance of trees. For. Ecol. Manag. 13:149–166.

Zeide, B. 1987. Analysis of the −3/2 power law of self-thinning. For. Sci. 33:517–537.