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DENSITY EFFECTS ON HEIGHT GROWTH AND ITS IMPLICATIONS FOR SITE INDEX PREDICTION AND GROWTH PROJECTION[1/]

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Abstract.--Four studies (two with loblolly and two with slash pine) show an effect of number of stems per acre on mean dominant and codominant height. One slash pine study averaged a 1-foot decrease in mean height at age 30 for each 100-tree increase in planting density over the range of 200 to 1200 seedlings per acre. Ignoring this density-height effect in a growth projection model developed from the same slash pine data resulted in over-estimating growth by as much as 46 percent.

INTRODUCTION

A long held tenet of our profession is that height growth is not affected by stand densities inside the range encountered in properly managed stands. This doctrine provides the foundation for the site index (SI) model, which ignores effects of density on height and assumes that productivity can be estimated from height growth alone. The consequence is an inability to separate effects of site productivity and density on height growth.

The only way to break this circular entrapment of assumption is to make a rigorous test by applying density treatments to plots so similar in topography, soil, and past use that they can be assumed to have equal productive potential. Randomized complete block (RCB) experiments that have planting spacings as treatments would offer data to search for a density-height effect. The degree to which site productivity differences are separated from the effects of density on height growth is directly proportional to the uniformity of plots within blocks. Unfortunately, blocks in spacing studies must be quite large and so plots are not necessarily as uniform as we would like. Nevertheless, lacking better data, we examined density-height trends in four studies, two loblolly pine spacing studies, a slash pine precommercial thinning study, and a slash pine spacing study. The objective here is twofold; first, to verify or reaffirm (depending on your persuasion) the existence of a density-height effect using several independent studies, and second, to use the slash pine spacing data to measure the effect of the density-height relation on prediction accuracy for periodic volume increments from yield models that use SI as a predictor (or driving) variable.

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EXAMPLES OF DENSITY-HEIGHT EFFECTS

Eighteenth-year measurements are available from an unpublished loblolly pine spacing study located on the Santee Experimental Forest, in Berkeley County, South Carolina. The study contains eight spacings consisting of 15x15, 11x11, 9x9, 7x7, 6x6, 5x5, 4x4, and 3x3 feet, replicated four times in 7-acre blocks. Mean total heights of the five tallest sample trees on each treatment plot are 56, 52, 58, 54, 53, 52, 49, and 45 feet, respectively. Although a trend of decreasing mean height with increasing planting density is apparent, we believe it is partly obscured by variation resulting from differences in soil type and drainage within blocks.

A second loblolly spacing study is on the Calhoun Experimental Forest on Piedmont soils near Union, South Carolina. It consists of four blocks, each with four spacings of 12x12, 10x10, 8x8, and 6x6 feet. Means of the five tallest sample trees from the 20-year measurements reported by Harms and Lloyd (1981) are 65, 63, 60, and 59 feet, respectively. A relationship of decreasing mean height with increasing planting density is also present in these data, and this effect is occurring over a more narrow density range than the first study.

From an RCB-designed, slash pine precommercial thinning study, Jones (1977) reported a linear relationship (R^2=0.903) of mean dominant and codominant height (H) over present number of trees at age 23. It might be argued that such an effect is expected from the wide density range in his experiment (279 to 5802 trees per acre at age 23), but a subset of these data with numbers of trees in the range of 279 to 2126 per acre produced a slope of -0.69 feet for each 100-tree increase on density and an R^2 of 0.858. This regression predicts a 4.2 foot decrease in mean H when density at age 23 is increased from 300 to 900 trees per acre.

The fourth study is with slash pine on the Holt Walton Experimental Forest, near Cordele, Georgia, in the middle Coastal Plain. It consists of two blocks planted at spacings of 15x15, 7.5x15, 10x10, 6x12, 8x8, 5x10, 6x8, and 6x6 feet. Table 1 presents the intercepts and slopes from linear regressions of mean H over number of planted seedlings (hundreds per acre) for ages 10, 15, 20, 25, and 30. The decrease in mean H is small at age 10, but by age 30 increases to 1-foot per 100-tree increase in planting density in the range of 200 to 1200 seedlings per acre.

A summary of part of the mean H data from the slash pine spacing study is given in Table 2. We assume that the observed trends in Table 2 represent effects of density on height growth and not differences in SI. This assumption of uniform site potential of plots within blocks is supported both by the closeness of the mean H values at age 10 (except for the 6x6 spacing where competition was fairly advanced by age 10) and the smoothness of the linear relations of mean H over planting density. These mean H and stand age (t) data are used with Bennett, McGee, and Clutter's (1959) old-field, plantation SI model to produce the SI-over-time data in Table 3. Stability of SI over time means the associated spacing has a height-over-time curve similar to that of the SI curve.

Table 1.--Estimates of linear regression coefficients for predicting mean dominant and codominant height from number of planted seedlings per acre.

Age (yrs)	Intercept	Slope
	Ft	Ft/100 seedlings
10	33.21	-0.2479
15	49.59	-0.5370
20	61.01	-0.8348
25	69.12	-0.9637
30	73.35	-1.0226

Table 2.--Mean dominant and codominant heights over time from slash pine spacing study.1/

Age (yrs)	Planting spacing (ft x ft)							
	15x15	7.5x15	10x10	6x12	8x8	5x10	6x8	6x6
	Height (ft)							
10	31.8	32.6	32.8	32.2	31.4	30.6	31.6	29.8
15	47.5	48.6	47.6	45.8	46.5	44.6	44.8	42.9
20	58.8	58.6	58.5	54.6	55.2	53.2	54.0	51.2
25	67.2	65.8	65.8	62.0	61.8	60.0	62.3	57.2
30	70.6	70.2	69.6	66.5	65.8	64.2	65.4	60.4

1/Values shown are averages for two blocks.

Table 3.--Base-age-25 site index estimates made over time on plots with different planting densities.1/

Site index prediction age (yrs)	Planting spacing (ft x ft)							
	15x15	7.5x15	10x10	6x12	8x8	5x10	6x8	6x6
	Site index (ft)							
10	67.1	68.8	69.2	68.0	66.3	64.6	66.7	62.9
15	66.2	67.7	66.3	63.8	64.8	62.2	62.4	59.8
20	66.6	66.4	66.3	61.8	62.5	60.3	61.2	58.0
25	67.2	65.8	65.8	62.0	61.8	60.0	62.3	57.2
30	65.0	64.6	64.1	61.2	60.6	59.1	60.2	55.6

1/Values shown are averages for two blocks.

GROWTH PREDICTION BIAS

Occurrence of effects like those illustrated above invalidates the foundation on which the SI model rests. This means that as a classification tool SI will be either over-estimated or under-estimated, depending on whether observed density is less than or greater than that density whose corresponding height-over-time curve equals that of the SI model. On the other hand, the effect of density on SI is not a problem in fitting yield models because SI is essentially a measure of dominant stand height, and as such will always be a highly significant variable in any yield model. The resulting model will always predict well for the SI, age, and density combinations at given points in time. The problem comes when the model is used to make predictions over time.

We evaluated the time related problem by fitting a yield model to our slash pine spacing data, and then comparing actual growth with predictions from the model. The 16 (8 spacings x 2 blocks) plots were measured 16 times, at ages 10 through 22, and at 25, 28, and 30. This produced 256 observations of total cubic foot volume per acre (V), stand age (t), SI (S) and merchantable basal area per acre (B_m). They were fit using the model

$$\ln(V) = \beta_0 + \beta_1 S + \beta_2 t^{-1} + \beta_3 \ln(B_m) \qquad (1)$$

and yielded $\hat{\beta}_0 = 3.1508844$, $\hat{\beta}_1 = 0.02566564$, $\hat{\beta}_2 = -19.403421$, $\hat{\beta}_3 = 0.82870861$, and an $R^2 = 0.993$. As you would expect from such a high R^2, yield predictions checked back very closely with observed volumes; so we concluded that the model is good.

The fitted yield model was next used to predict total cubic foot growth by incrementing stand age (t) and basal area (B_m). Basal area increment comes from observed density-over-time data presented in Table 4. The above prediction process assumes SI is constant for any growth period. For this research we used the mean SI at age 10 as this constant SI value (66.7 feet at age 25). Of course, Table 3 contradicts this assumption so the above defined predicted growth was compared with actual growth obtained by using stand age and basal area, plus the observed SI values from Table 3.

Differences in these two volume increments (Predicted-Actual) are presented in Table 5. They result from assuming SI does not change over the projection period. The bias increases with decreasing spacing from the widest spacing (15x15) because height growth associated with this spacing most nearly matches that of Bennett, McGee, and Clutter's SI model. The trend of increasing bias with increasing length of the projection period is due to the cumulating effect over time of density on height growth. Table 6 presents these volume growth differences as percentages of actual volume growth defined in the previous paragraph.

CONCLUSIONS

Four independent studies show height growth of both loblolly and slash pine to be reduced as stand density increases inside a range considered proper forest management. Existence of this effect repudiates a foundation principle of SI, which in turn invalidates it as a determinant in studying growth and yield relations over time. Specifically, we showed that substantial bias can result in periodic growth predictions from a yield model built on data containing an effect of density on height, even when the model otherwise fits the data closely. The direction of the bias will depend on where in the density range height growth matches the SI curve. In this example it occurred at the widest spacing, but it could occur at any stocking level, depending on the properties of the two data sets used to fit the yield and SI models.

Any attempt to modify SI to handle density would be self defeating in that the purpose and primary defense of SI has been its independence from effects of density. Such an effort would also validate the arguments of those who would use volume to measure productivity of forested sites.

This along with the poor precision of the SI predictor (Lloyd and Hafley 1977, Lloyd 1981, Lloyd, Muse and Hafley 1982) suggests that we should be investigating alternative methods of using measurements of trees to establish forest site productivity.

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Table 4. Mean merchantable basal area per acre.1/

Age (yrs)	Planting spacing (ft x ft)							
	15x15	7.5x15	10x10	6x12	8x8	5x10	6x8	6x6
	Basal area (sq ft)							
10	44	70	74	82	84	82	95	61
15	71	102	108	114	128	125	137	122
20	96	121	132	131	147	143	154	147
25	111	135	140	138	150	145	153	154
30	114	137	135	132	140	133	134	144

1/Values shown are averages for two blocks.

Table 5.--The amount merchantable cubic foot volume (o.b.) is overestimated when the density-height effect is ignored.

Growth period (yrs)	Planting spacing (ft x ft)							
	15x15	7.5x15	10x10	6x12	8x8	5x10	6x8	6x6
	Volume (cu ft)							
10-15	21	-58	24	173	127	284	294	413
10-20	7	27	39	442	421	608	562	819
10-25	-51	107	110	539	600	778	552	1116
10-30	197	282	343	684	790	923	807	1373

Table 6.--Percentage by which growth is over-estimated when the density-height effect is ignored.

Growth period (yrs)	Planting spacing (ft x ft)							
	15x15	7.5x15	10x10	6x12	8x8	5x10	6x8	6x6
	Percent							
10-15	2	-4	2	15	9	24	23	34
10-20	0	1	2	21	17	28	24	37
10-25	-2	3	3	19	19	28	18	38
10-30	6	7	9	22	24	31	27	46