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DESIGN DIFFICULTIES IN STAND DENSITY STUDIES

Abstract.-Designing unbiased stand density studies is difficult. An acceptable sample requires stratification of the plots of age, site, and density. When basal area, percent stocking, or Reineke's stand density index is used as the density measure, this stratification forces a high negative correlation between site and number of trees per acre. Mortality in trees per acre is correlated with real density (basal area, percent stocking). As a result, in a controlled study, mortality in trees per acre is about the same on all sites. This, in turn, means mortality in cubic volume is strongly and positively correlated with site. The measured effect of site on growth is greatly reduced. When dealing with merchantable volumes, ingrowth is negatively correlated with site, and this also reduces the measured effect of site on growth. Although these problems cannot be eliminated, this paper offers suggestions for reducing their effect.

In this highly competitive industrial age, the production of a low-value commodity-wood-on high-value land through the use of high-value labor, money, and equipment requires a thorough understanding of volume production under a variety of stand conditions. With a knowledge of stand response under varying conditions, management can select the alternative best suited to its product or financial objective. Studies must be designed that will measure, with a reasonable degree of accuracy, growth and total yield over a rather broad range of age-site-density schedules. The most common study design requires the establishment of permanent plots which are remeasured and cut to specified densities at regular intervals. An acceptable sample requires stratification over age, site, and stand density. This need for stratification, and the results, is the major point I wish to review.

The Rectangular Distribution

In order to evaluate growth properly for a variety of conditions, the familiar rectangular distribution is used as a guide to insure acceptable coverage of the ages, densities, and sites available for sampling (table 1). The perfect sample would include one or more plots in each cell of this table. Obviously, not every cell can be filled. For example, one does not expect 165 square feet of basal area, or more, at a young age, and especially on the lowest site. For the sections of the rectangular distribution that are difficult to fill, the usual practice is to accept whatever can be found in these areas, regardless of how the remainder of the sample may be distributed. The lack of uniformity in the distribution, however, can lead to difficulties.

isolated Plot Effects

For evaluation of certain parameters, isolated plots in the sample distribution may offer no particular problem; but for others, trouble can arise. Site index is an example. Some years ago, the Southeastern Forest Experiment Station established a stand density study in slash pine plantations in the coastal plain areas of Georgia and Florida. Among other objectives, we wished to determine whether or not growth and yield differed significantly among the three distinct geographic provinces within the sample area—upper, middle, and lower coastal plains. As a first test? site index analyses were run for each province by the standard height-age model:

$$\text{Log height} = a + b \frac{1}{\text{age}}$$

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Table 1. --The rectangular distribution used as a guide for sampling age, site, and stand density and growth and yield research

Age	Site	Stand density (square feet of basal area)					
		40	65	90	115	140	165
	40						
	50						
10	60						
	70						
	80						
	40						
	50						
15	60						
	70						
	80						
	40						
	50						
20	60						
	70						
	80						
	40						
	50						
25	60						
	70						
	80						
	40						
	50						
30	60						
	70						
	80						

Formal tests indicated a significant difference between the upper coastal plain regression and the other two, but no difference between the middle and lower provinces. Because the average number of trees per acre in the upper coastal province was 64 percent greater than in the middle and lower coastal plains, number of trees per acre was added as a second independent variable to each regression. The density variable was highly significant in the upper coastal plain, but nonsignificant in the other two areas. Inspection of the density-site relationship for the upper plain area showed that all plots except two were site 50 and above, and had 800 trees per acre or less (table 2). The two remaining plots were sites 30 and 40 with 900 and 1,100 trees, respectively. A distribution of this nature led to the suspicion that these two high-density, low-site plots were producing an exaggerated density-height interaction effect. This proved to be the case. If these two plots were eliminated from the analysis, arbitrarily raised to site 70, or reduced to an average density of 500 trees per acre, the density variable in the site index analysis became nonsignificant; and significant differences in site index regressions among provinces disappeared. Although this distribution probably would not affect volume relationships to the degree that it affected site classification, it does illustrate the point that a uniform distribution is desirable, and even necessary, for certain purposes.

Residual Density Effects

TREES PER ACRE. Stratification of residual densities over the range of available sites produces situations that can also be quite troublesome. Basal area, cubic volume, or percent stocking is generally used to evaluate growth in relation to stand density. As a necessity: we specify that, insofar as possible, plots of a given residual density be established on all available sites. This specification automatically forces a correlation between number of trees per acre and site, regardless of the density measure used. At any given age, the number of trees needed to produce a given basal area will be much larger on site 60 (50-year basis), for example, than on site 90. As evidence, the mean residual number of trees and mean square feet of basal area per acre at time of establishment for a growing space study in natural slash pine stands were as follows:

Site index class (50-year basis)	Trees	Basal area
	(Number)	(Square feet)
60	547	107
70	460	89
80	372	90
90	278	99
100	266	108

This correlation of number of trees per acre and site can create problems. As an example, one ordinarily expects mortality to be correlated with number of trees per acre. In a controlled stand density study, however, this is not necessarily the case. In our study, mortality in trees per acre was practically the same on all sites, despite the fact that trees per acre was highly and negatively correlated with site:

Site index class (50-year basis)	Mean annual loss in trees per acre
50	9
70	7
80	9
90	8
100	8

One possible explanation for this is that total stocking is expressed through density measures (basal area, cubic volume, percent stocking) that reflect the degree of competition within the stand, and number of trees per acre is not a good comparative measure of competition.

As a result of the loss of the same number of trees per acre on all sites, there was a strong correlation between cubic volume mortality and site:

Site index class (50-year basis)	Mean diameter[1]	Mortality per acre
	(Inches)	(Cubic feet)
60	6.1	13
70	6.6	24
80	7.7	43
90	9.1	66
100	9.4	93

[1]These are mean values of plot mean diameters and are not values for the plot of mean basal area.

As site increased, average tree size increased, going from a diameter of 6.1 inches on site 60 to 9.4 inches on site 100. Given this condition, loss of the same number of trees on all sites meant cubic volume loss had to increase with site. It is axiomatic that if site and number of trees per acre are negatively and highly correlated-a situation that results from stratification of sample plots over site and density-mortality expressed in cubic volume must be highly and positively correlated with site, unless mortality in number of trees per acre is highly and negatively correlated with site.

Table 2. --Distribution of plots by site and density for the upper coastal plain province

Site	Trees per acre											Total
	100	200	300	400	500	600	700	800	900	1,000	1,100	
	Number of plots											
30									1			1
40											1	1
50				2	5	1	2					10
60			2	6	4	5	7	2				26
70			1	3	4	8	6	2				24
80				1	1			1				3
Total			3	12	14	14	15	5	1		1	65

INGROWTH. Another disturbing factor resulting from the forced correlation between site and number of trees per acre is the correlation that is also forced between site and ingrowth when merchantable volume is the unit of measure. A threshold diameter–usually 5 inches-is set up, and no volume is recorded for a tree until it enters this limiting diameter class. If good distribution over the age variable is attained, the amount of ingrowth over a given period on low sites can be much greater than that on the better sites. In our stand density study of natural slash pine, for example, the average sample on site 60 had 173 trees per acre below 5 inches in diameter. If all of these trees grow to the 5-inch class, ingrowth during the study period will equal about 4 cords. On the other hand, few of the plots on the better sites had trees below merchantable size at time of establishment. This is the result, of course, of two factors: (1) better growth on the high sites, and (2) more thinning on the higher sites to reduce them to the assigned basal areas, with the thinning generally from below.

The problem with ingrowth is that growth rates are inflated on the poor sites. If ingrowth occurred at about the same rate on all sites during the measurement period, there would be no problem. And the fact that the same amount of ingrowth that we experienced on the low sites may have occurred on the good sites prior to our measurement period is no ameliorating factor. We are measuring growth over a given period; and with ingrowth occurring on the poor sites and not on the better ones during the study period, growth is biased in favor of the low sites. This bias will hold beyond the point of ingrowth, because the inflated effect of the low sites will be built into the prediction model.

Discussion

These are some of the difficulties we at the Southeastern Forest Experiment Station have faced in growth and yield research. Can the impact of these situations be either avoided or reduced? Because stratification of the sample over age, site, and density is necessary, there seems to be no way to avoid the correlation between trees per acre and site. And because mortality in trees per acre appears to be related to basal area density and not necessarily to number of trees per acre, the correlation between site and cubic volume mortality may be difficult to avoid. Faced with these conditions, we must use every precaution to hold mortality within reasonable limits. If we can hold mortality in trees per acre to a low level, our problem will be greatly reduced.

If mortality is heavy, as in our stand density study of natural slash pine, growth rates will be drastically reduced. And if mortality in cubic volume is correlated with site-a seemingly natural result in stratified growth and yield studies-the effect of the site variable can be practically eliminated. Under these conditions, the full impact of site on growth can be estimated by: (1) using for analysis purposes only the trees that live through the growth period, or (2) using all trees and including the volume of trees that die during the growth period in the growth data. Either procedure requires that all trees be individually identified at each measurement period. If we eliminate from the analysis all trees that die during the growth period, then a question as to the appropriate residual density develops. Shall we use the residual basal area at time of establishment, or shall we eliminate the square footage of those trees that died during the measurement period? If, on the other hand, we include mortality in the basic volume data, growth will be overestimated by whatever might be considered normal mortality. Another weakness in this method, that is, including mortality in the growth data, is that any tendency for growth to culminate in relation to density and age is offset to some extent. Culmination will be delayed as long as all trees are alive and adding some volume, and we simulate this situation when mortality is included in growth data. The effect will be greatest in stands where mortality is associated with overstocking and culmination is approaching or at hand.

The answer to the question of how to handle mortality in growth analyses seems to depend on the extent of the loss. If mortality is light-only a few cubic feet per acre annually-then it might be ignored and the initial residual density employed in the analysis. If mortality is fairly heavy, however, and most especially if it is correlated with site, the only alternative is to include mortality in the volume growth data. Otherwise, any growth values established will have little validity.

The ingrowth problem will be with us as long as we use merchantability limits. However, we can account for this factor by permanently numbering each tree so that it can be identified at each measurement period. Growth on the merchantable trees can then be established by subtracting the volume of the trees that grew into merchantability during the growth period. An even more realistic approach would be to subtract the initial volume of each tree that grew into merchantability during the growth period from its final volume. Under this method, growth on the trees that grew into the threshold class during the measurement period would be accepted as bona fide merchantable growth; but the major volume of the tree, which was produced prior to the growth period, would be excluded.

A simple solution would be to measure total growth rather than merchantable increment. The disadvantage here, of course, is that salable volume is overestimated by the amount of nonmerchantable growth. Under certain conditions this might not be enough to cause serious error. There are situations, however, when the overestimate might cause problems. Another possibility is the development of merchantable-nonmerchantable ratios to reflect the amount of merchantable growth to expect when the residual stocking includes various amounts of nonmerchantable volume.

Summary

In summary, the evaluation of certain parameters in growth studies, particularly site index, requires a fairly uniform distribution of the sample over age, site, and density. This need for good stratification of the sample results in the following situations:

1. Trees per acre and site are strongly correlated.

2. If mortality is correlated with real density (basal area stocking), mortality in trees per acre will be approximately uniform over site.

3. Loss of the same number of trees on all sites results in an extremely strong correlation between cubic volume mortality and site.

4. As a result of the correlation between mortality and site, the effect of site on growth is reduced.

5. The correlation between trees per acre and site forces a correlation between ingrowth and site, and the real effect of site is again reduced.

Although the correlation between trees per acre and site cannot be avoided, permanent identification of each sample tree will permit an exact measure of mortality with respect to merchantable or nonmerchantable trees, and ingrowth can be handled in the most expedient manner.

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