Problems in Relating Soil to Site Index For Southern Hardwoods

BY
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Abstract. Various soil-site characters were correlated with height growth of *Liquidambar styraciflua* L., *Quercus falcata* var. *pagodaefolia* Ell., *Q. nigra* L., *Q. phellos* L., *Q. nuttallii* Palmer, *Fraxinus pennsylvanica* Marsh., and *Populus deltoides* Bartr. in the Midsouth. Equations developed by multiple regression, however, do not predict site index of new populations with sufficient precision over a large area. Incomplete sampling of the conditions under which southern hardwoods grow may have contributed, but the failure resulted mainly from the inability to measure the true causes of productivity—soil moisture and nutrient availability during the growing season, soil aeration, and physical condition including root growing space.

Additional key words. Site classification, soil-site classification.

A FORESTER cannot achieve maximum productivity on a site without reliable predictions of the performance of trees of all the species that might be grown there. Past abuses make the trees in many southern hardwood stands poor indicators of potential productivity. Thus, scientists and land managers have long placed their hopes for accurate predictions upon soil and topographic features. They have often been disappointed, and the present paper contains little to encourage them.

Until recently, most site classifications for southern hardwoods were based on local topography and land forms (Putnam 1951, Putnam *et al.* 1960). Early efforts to include soil characters in site classifications were made by Turner (1937) and Donahue (1937). Donahue examined chemical and physical properties in an attempt to explain differences in growth of oaks on Sharkey clay in the lower valley of the Mississippi River and on Lufkin clay in the upland flatwoods of the State of Mississippi. His approach failed, perhaps because inherent moisture conditions of the sites were not considered. Turner (1937), using a subjective approach, concluded that "soil features influencing available water seem to be more influential than others in determining rate of growth. . . ." The factors he listed as being important for hardwood growth were slope as it affects drainage, exposure, depth of soil, and physical structures of soil horizons.

The first attempt to correlate southern hardwood tree growth with site factors over a wide area was begun by Beaufait (1956). He found that clay content and topographic position were the best indicators of willow oak (*Quercus phellos* L.) site quality on Mississippi River soils. In other river and stream bottoms, the amount of available potassium and topography were the characters most closely related to site index for willow oak.

The objective of the present study, a sequel to the work of Beaufait (1956), was to develop a means for accurately estimating site index from quantifiable

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soil-site characters. It was planned to relate these factors to productivity for all commercially important species in the southern hardwood region. Work was stopped, however, when results turned out so poorly for the first seven species—sweetgum (*Liquidambar styraciflua* L.), eastern cottonwood (*Populus deltoides* Bartr.), willow oak, cherrybark oak (*Quercus falcata* var. *pagodaefolia* Ell.), water oak (*Q. nigra* L.), Nuttall oak (*Q. nuttallii* Palmer), and green ash (*Fraxinus pennsylvanica* Marsh.).

As work on individual species was completed, field guides and other practical information were published for forest managers (Broadfoot 1960, 1961a, 1961b, 1961c, 1963, 1964, Broadfoot and Krinard 1959). These guides presented subjective methods translated from, or closely related to, soil series and measurable soil-site factors. But until objectively measurable variables can be discovered which are correlated with tree performance, the prediction of site index from soil factors will not be completely sound.

This paper reports the problems encountered in developing site index prediction equations with generally accepted or standard procedures, and discusses some of the reasons for the imprecise results. The equations presented now do not appear to be more accurate than the subjective methods, and they are more difficult and time consuming to apply.

Procedures

Field Sampling. A total of 739 1/5-acre circular plots were located in six States

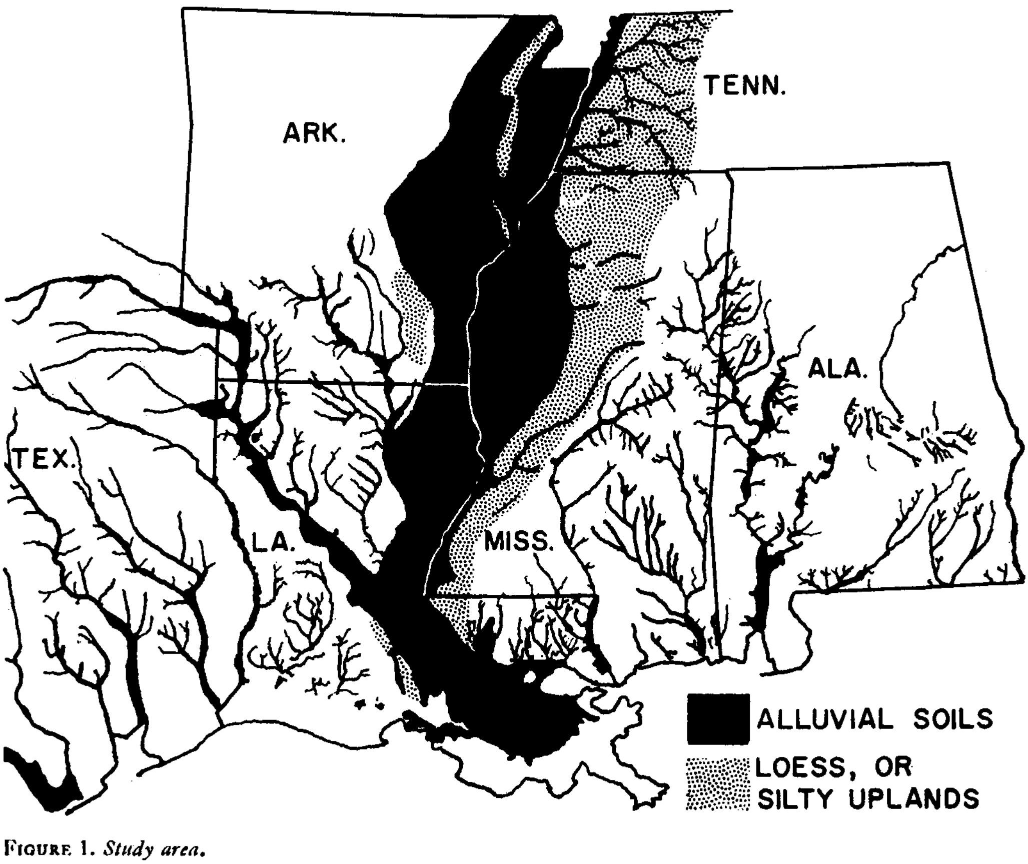

FIGURE 1. *Study area.*

(Fig. 1). Most were on Mississippi River alluvium; some were on soils of other streams, on terraces, and on loess. Other than in areas of loess, no attempt was made to sample uplands, which are usually better suited for pine than hardwoods. Each plot had one or more of the priority species under study.

Sampling was restricted to areas of uniform soil which supported well-stocked, even-aged stands that showed no visible signs of cutting or burning. The minimum stand stocking that was accepted was 70 ft^2/acre of basal area. To minimize the effects of errors in site curves, site index at age 50 was estimated only from trees that were 40 to 60 yr old for all species but cottonwood. In addition, only trees that appeared to have always been dominant or codominant were selected. For eastern cottonwood, only trees that were 20 to 40 yr old were measured to estimate height at 30 yr. Each sample tree's total height and diameter and age at breast height were measured.

For each study species, from 10 to 20 sample trees growing on a wide variety of soils were felled and sectioned to establish appropriate height-over-age curves. On each sectioned tree, age was counted at intervals of 8 ft from a 1-ft stump to the top. The curves, published previously except for Nuttall oak and green ash, were used to make the minor adjustment of current heights to heights at age 50 (30 for cottonwood). A large number of seedlings and saplings were cut to determine the time required for members of each species to reach breast height.

Bulk soil samples were taken at depths of 0–1, 1–2, 2–3, and 3–4 ft. Each depth was sampled at two points on each plot, and samples for the corresponding depths were composited. Core samples were also taken at depths of 0.5, 1.5, 2.5, and 3.5 ft at two points on each plot using a modified San Dimas soil sampler (Andrews and Broadfoot 1958).

Physiographic features, soil series and phase, depth to mottling, depth of topsoil, presence of pans, and inherent moisture class (moist or dry) were also recorded for each plot. Depth to mottling and depth of topsoil (A-horizon) were measured to the nearest inch.

Sites were classed as either moist or dry, depending upon moisture availability during the growing season. A site was considered moist if it: (1) was level or received surface water from the surrounding area, (2) was in a narrow branch or creek bottom, (3) was on a lower slope, (4) had a true water table within 4 ft of the ground surface, or (5) sloped more than 17 percent in a loess area. Steep slopes on loess soil are usually the sides of huge old gullies, and the loose silty material receives moisture more readily than clay and holds it more strongly than sandy soils. Sites were also considered moist if capillary moisture above the true water table or mean low water in adjacent streams or lakes extended into the root zone.

A site was considered dry if it: (1) was sloping or on a ridge in a broad river bottom, (2) was situated so that floodwater or heavy rains drained off (other than as specified for moist sites), or (3) contained a pan.

Laboratory and Statistical Analysis. The bulk soil samples were air-dried and sieved through a 2-mm screen. The hydrometer method was used in particle-size analysis. Moisture equivalent and imbibitional moisture were determined by centrifuging before and after saturating with water and then xylene. Soluble salt concentration was determined by electrical conductivity; 15-bar tension, by pressure membrane technique; organic matter, by the wet combustion method; pH, by glass electrode; exchangeable K and Na, by extraction with slightly acid ammonium acetate and flame spectrophotometry; and dilute acid-fluoride extractable P, by the ammonium molybdate-sulphuric acid method with spectrophotometry. Bulk density, total pore volume, and moisture retained at 60-cm water tension were determined in soil cores. Available water capacity was then calculated as the difference in moisture retained at 60-cm tension and 15-bar pressure.

The relationships between site index and the measured soil and site characters were explored graphically and by multiple regression. The numerous soil characters were first screened for promising ones by plotting them against site index. The site index values plotted were obtained from height-over-age curves developed from sectioned trees. Up to 40 independent variables were selected for each species for further study. Because methods of analysis differed somewhat by species, they are reviewed briefly in the results for individual species.

Results

Sweetgum. Thirty-four variables were examined by a modified stepwise regression analysis (Table 1). Subscripts are the

TABLE 1. Independent variables in site-index regression analyses for each species.

Variable	Symbol	Unit	Species and soil layer[1]						
			Sweet-gum	Cherry-bark oak	Water oak	Willow oak	Nuttall oak	Green ash	Cotton-wood
1/total age of tree(s)	1/age	Ratio	X	—	—	—	—	—	—
Sand	S	% by wt.	—	0–2	—	4	—	—	—
Silt	Si	% by wt.	1,2,3,4	—	0–4	4	—	—	—
Clay	C	% by wt.	1,2,3,4	0–2	—	4	4	1	3
Silt + Clay	(Si + C)	% by wt.	—	—	—	—	4	1	3
Bulk density	BD	G/cc	1,2,3,4	—	—	—	—	0–4	—
Organic matter	OM	% by wt.	1,2,3,4	—	1	—	—	—	3
Topsoil, depth of	TS	Inches	—	X[2]	X	—	—	—	—
Fragipan, with or without	FP	([3])	—	X	X	X	—	—	—
Mottling, depth to	MOT	Inches	—	X[4]	X	X	X	—	X
Imbibitional water	IW	% by wt.	1,2,3,4	0–2	—	—	—	—	3
15-bar moisture	BM	% by wt.	—	—	0–4	—	—	—	—
Available water capacity	AWC	% by wt.	—	—	—	—	0–4	—	—
AWC_1 × Jan.-July rainfall	AWC_1 × JJR	—	—	1	1	—	—	—	—
Inherent moisture of site	IM	([5])	—	X	X	X	X	X	—
Soil reaction	pH	Number	1,2,3,4	—	—	4	1	1	3
Readily extractable phosphorus	P	Lb/acre	1,2,3,4	—	—	4	4	1	3
P in soil layers	P/P	Ratio	1/4	—	—	—	—	—	—
Exchangeable potassium	K	Lb/acre	1,2,3,4	—	—	4	4	1	3
Exchangeable sodium	Na	Lb/acre	—	0–2	0–4	—	—	1	—
Soluble salts	SS	Mmhos/cm	—	—	—	—	4	1	—

[1] The numbers in the data columns are the lower limit of the layers sampled, in feet.

[2] Coded as: 0 = >6″, 1 = 5″, 2 = 4″, 3 = 3″, 4 = 2″, and 5 = 1″.

[3] Coded as 0001 or 0000.

[4] Coded as: 0 = >24″, 1 = 18 to 24″, 2 = 12 to 18″, 3 = 6 to 12″, 4 = 0 to 6″.

[5] Coded as ±0001.

lower limits of the layers sampled. Thus, C_1 is the clay content of the uppermost foot of soil.

The sweetgum data from 104 plots were processed on an IBM 650 computer, using a program developed by Professor G. M. Furnival, Yale University School of Forestry. For sweetgum only, log height and 1/age were substituted for site index. The variable 1/age was fitted first. Then new variables were added one at a time in the order that most reduced the sum of squared residuals about the regression fitted in the previous stage.

The resulting equation, with $clay_4$ and $potassium_4$ as the significant soil variables, was:

$$\text{Log height} = 2.102389 - 4.795160 \frac{1}{\text{age}} - 0.001904C_4 + 0.000154K_4$$

Thirty-four percent of the variation in height was associated with this equation ($R = 0.58$). For predicting site index, age was set at 50:

$$\text{Log site index} = 2.006486 - 0.001904C_4 + 0.000154K_4$$

Height-age curves from the data on sectioned trees (Broadfoot and Krinard 1959) were fitted by age rather than by the method of Bruce and Schumacher (1950, p. 393–397) because trees representing poor sites were older than trees representing good sites.

The equation was tested for predicting height of sweetgum on 126 sample plots which were not used to develop the relationship (Table 2). The correlation coefficient (r) between measured and predicted values was 0.21. The average predicted site index was 93 ft ± a standard deviation of 8 ft; actual values averaged 94 ± 10 ft. Sixty percent of the predicted values were within 8 ft of the actual values. Thus, 40 percent of the site index predictions could be off by more than a 16-ft log for each tree on the plot. Phillips and Markley (1963), working only with soils on the Coastal Plain in New Jersey, concluded that sweetgum site index could be satisfactorily estimated from an equation that included clay and fine-sand contents. This equation accounted for a greater percentage of variation than the one reported here, probably because of the limited area on which their equation is based.

Cherrybark Oak. Site index values for cherrybark oak were determined from age and height data on 113 plots and from hand-fitted curves of the data obtained by stem analysis of sample trees (Broadfoot 1961a).

TABLE 2. Accuracy of height-prediction equations on new populations.

Species	Original analysis: Plots	R^2	Standard error	New population: Plots	Actual mean	Predicted mean	Accuracy: r	Within 5 ft	Within 8 ft	Maximum difference
	No.	*%*	*Ft*	*No.*	*Ft*	*Ft*		*%*	*%*	*Ft*
Sweetgum	104	34	± 8	126	94 ± 10	93 ± 8	.21	40	60	28
Cherrybark oak	113	39	± 9	66	97 ± 9	96 ± 5	.43	53	74	27
Water oak	113	32	± 8	125	93 ± 6	93 ± 9	.47	54	73	22
Willow oak	150	43	± 9	65	92 ± 9	92 ± 6	.44	48	66	18
Nuttall oak	76	30	± 9	51	94 ± 12	94 ± 6	.60	37	59	18
Green ash	81	14	±10	53	82 ± 10	97 ± 4	.07	15	28	38
Cottonwood	102	45	±10	0	—	—	—	—	—	—

Hand screening reduced the number of variables from 74 to 9 that appeared promising. A multiple regression program developed by Grosenbaugh (1958) was used to analyze these nine (Table 1).

The multiple-regression analysis yielded the equation:

$$\text{Site index} = 103.66 - 11.04\text{FP} - 2.67\text{MOT} - 6.19\text{TS}$$

Presence of fragipan decreased site index by 11 ft. Due to the system of coding, depth to mottling and depth of topsoil were negatively correlated. Increasing code values of each variable signified less depth and thus decreased site index. Standard error for each estimated value by this equation is 9 ft, $R = 0.62$; and 39 percent of the variation in site index was associated with the three independent variables. All nine factors accounted for only 48 percent of the variation. Prediction values of site index for individual trees could be off by as much as 20 ft at the 95-percent confidence level.

The equation was tested on 66 sample plots not used in its development (Table 2). The correlation coefficient (r) was 0.43. The average predicted site index for the 66 samples was 96 ft $\pm$ a standard deviation of 5 ft. Actual values averaged 97 $\pm$ 9 ft. Seventy-four percent of the predicted values were within 8 ft of the actual values, and 53 percent were within 5 ft.

Hebb (1962), in a study confined to soils derived from loess and measurements made on only 21 cherrybark oak trees, found surface drainage to be the most important determinant of site index. He also reported that basal area was significantly associated with site index, but subsequently discounted this factor because of the probable lack of causal relationship between it and height growth.

Water Oak. Site index values for water oak were determined, as for other species, from growth curves developed from stem analysis of sample trees growing on widely divergent sites (Broadfoot 1963). Site and tree characters were examined on 113 plots.

After screening, nine variables were studied further by multiple regression analysis (Table 1). All nine variables accounted for 39 percent of total variation ($R = 0.62$). Further examination of the 511 regressions showed that the most useful for predicting water oak site index was:

$$\text{Site index} = 87.18 - 13.34\text{FP} + 1.558\text{TS} - 0.0264\text{Na}_{0\text{-}4} \quad (R = 0.57)$$

The standard error of estimate is $\pm$8 ft. The negative relationship between exchangeable sodium in the soil and height growth probably reflects poor drainage.

The equation was tested on 125 new plots (Table 2). The correlation coefficient (r) was 0.47. The average predicted water oak site index for the 125 plots was 93 $\pm$ 9 ft. Predicted site index was within 5 ft on 54 percent of plots.

Willow Oak. Site index estimates of willow oak were made from the straight-line growth factor of 0.85 ft per year, as calculated by Beaufait (1956). Data from 66 new plots were combined with Beaufait's data; a total of 150 plots were analyzed.

After preliminary screening, nine variables were analyzed by multiple regression (Table 1). All variables accounted for only 45 percent of total variation ($R = 0.68$). The equation selected as the most useful and/or practical was:

$$\text{Site index} = 96.90 - 0.1566\text{C}_4 + 0.3276\text{MOT} - 23.91\text{FP} - 4.49\text{IM} \quad (R = 0.65)$$

The standard error at the mean is $\pm$9 ft. Predictions from this equation may err by more than one 16-ft log.

The equation was tested on 65 new plots (Table 2). The correlation coefficient (r) was 0.44. The average predicted value was 92 ± 6 ft; the actual, 92 ± 9 ft. Predicted site index was within 5 ft on 48 percent of plots, and within 8 ft on 66 percent. The maximum difference between predicted and actual site index was 18 ft.

Nuttall Oak. Nuttall oak site indexes were estimated from the curve developed by stem analysis (Fig. 2). Soil-site and tree data were collected from 76 plots.

From 39 variables, 9 were selected by the BMD 02R stepwise regression program for further regression analysis (Table 1). These were programmed through 511 multiple regressions by the REM program of Grosenbaugh (1958). All variables accounted for only 34 percent of total variation, $R = 0.58$. The equation

$$\text{Site index} = 120.5 - 0.385(\text{Si} + \text{C})_4 - 0.036\text{SS}_4 + 0.443\text{AWC}_{0\text{-}4}$$

$$(R = 0.54)$$

was selected for practical field use.

On 51 new plots, the average predicted value was 94 ± 6 ft (Table 2). The actual measured values average 94 ± 12 ft. Of the predicted values, 37 percent were within 5 ft of measured values, and 59 percent were within 8 ft. The linear correlation coefficient (r) between predicted and actual values was 0.60. The maximum difference between predicted and actual values was 18 ft.

Green Ash. Heights were adjusted to age 50 with the growth curves constructed

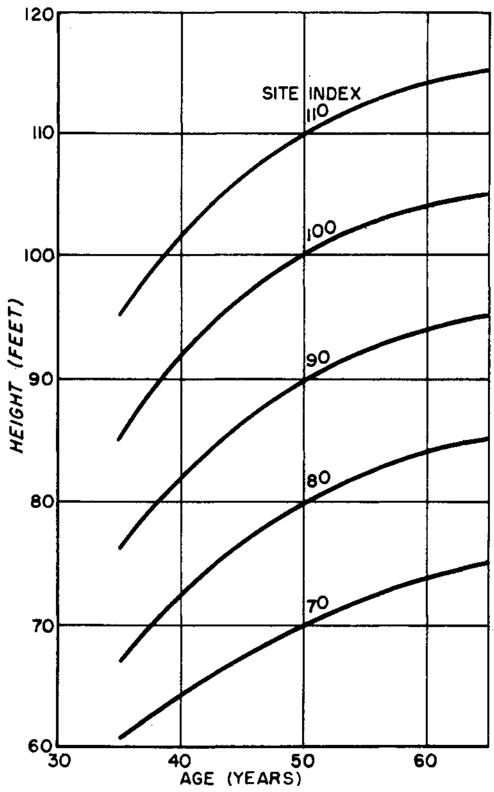

FIGURE 2. *Height adjustment curves for Nuttall oak.*

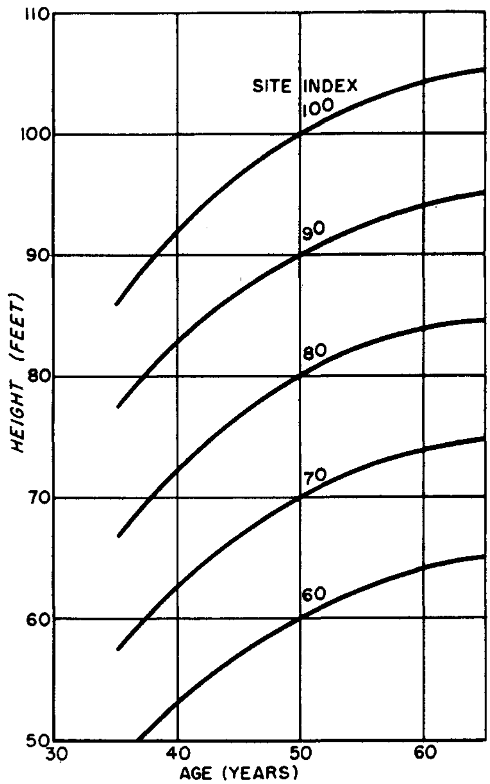

FIGURE 3. *Height adjustment curves for green ash.*

from data on sectioned trees (Fig. 3).

With site index as the dependent variable, data from 81 plots were analyzed by multiple regression. Thirty-nine independent variables were screened to obtain the most important nine for REM multiple regression analyses (Grosenbaugh 1958) (Table 1). These variables accounted for only 20 percent of total variation, the lowest of all species studied.

The best three-variable equation

$$\text{Site index} = 119.9 - 0.208C_1 + 0.292pH_1 - 0.241BD_{0\text{-}4} \quad (R = 0.38)$$

had a standard error of estimate of ± 10 ft. The relationship was not significantly improved by addition of another variable.

Easily determined field factors other than texture and pH were unimportant. Inherent site moisture was the least important variable of the nine selected. The poor correlation between expressions of moisture and site index is probably due to the nature of the sites examined. Slightly more than 75 percent of the plots were on moist, poorly drained soil. Another study showed that green ash is very responsive to changes in moisture conditions (Broadfoot 1967).

The equation was tested on 53 new plots (Table 2). The correlation coefficient (r) was 0.07. The average of the predicted values was 97 ± 4 ft; the true average was 82 ± 10 ft. Of the predicted values, only 15 percent were within 5 ft of the actual, and 28 percent within 8 ft. The maximum difference between predicted and actual values was 38 ft.

Cottonwood. Cottonwood growth curves were developed from data on sectioned trees that were from 20 to 40 yr old (Broadfoot 1960). Soil, site, and tree data were collected on 102 plots.

A total of 29 variables were selected as promising. The best single correlation coefficient (r) between these 29 variables and site index was 0.54. A stepwise regression analysis of variables measured in each 1-ft soil layer showed that measurements taken in the 2- to 3-ft layer were the best indicators of site index (Table 1). The equation was:

$$\text{Site index} = 62.9 - 0.363C_3 + 0.281(Si + C)_3 + 5.54pH_3 - 0.033P_3 \quad (R = 0.67)$$

The standard error of estimates was ± 10 ft. The equation was not tested on new plots.

Discussion

This exploratory study was an attempt to develop a model or models through multiple regression for each species-soil factor relationship. The models produced have not fit very well the data from which they were derived. None of the derived equations predicted site index with sufficient precision for investment planning. Incomplete sampling of the conditions under which southern hardwoods grow may have contributed, but it seems the failure resulted mainly from the inability to measure the true causes of productivity. Almost certainly, productivity is determined by moisture and nutrient availability during the growing season, soil aeration, and physical condition including root growing space. Apparently, pH, acid-fluoride extractable P, exchangeable K and Na, depth of topsoil, and clay content do not indicate how much of each nutrient is available to the tree. Neither do available water capacity, inherent moisture condition, presence of a pan, and texture show how much moisture is available during the growing season.

Available moisture probably is the single most important determinant of productivity. Because of the restricted use that can be made with the laboratory-measured available water capacity (AWC) of specific soils, a classification of the available moisture status inherent to soil sites was attempted. Available water capacity emerged in only one equation, that of Nuttall oak, as an important factor. In fact, it did not even survive preliminary screening in the regression analysis for any of the other species. The IM factor also emerged in the final equation for only one species, but rated special consideration for further analysis for five of the seven species. Inherent moisture, even though crudely classified here as either "moist" or "dry," did indicate better than AWC, over the full range of physiographic site conditions, soil water available to trees during their growing seasons. Available water capacity is influenced strongly by soil pans, physiography, and rainfall in many cases, and seldom represents the amount of available water.

The 3- to 4-ft depth was the most influential in the sweetgum, willow oak, and Nuttall oak equations. The entire 4 ft of soil were most important for water oak. The third layer was important in the cottonwood equation, the surface 2 ft in the cherrybark oak, and the surface foot in the green ash. The reasons for the differences in key depth are not known, but possibly the significant depths reflect major rooting zones. Confusing results such as these preclude satisfactory conclusions and add to the complexity of estimating site index from soil-site factors.

The study was planned to measure soil conditions in proportion to their occurrence. Thus, the full range of conditions probably was not represented. The 739 plots were on 55 soil series. Sharkey clay was sampled 67 times, but 31 percent of the series were sampled only once. Sharkey showed up often because it is a common forest soil. It is difficult to farm and, thus, is seldom cleared for plowing. The soils sampled only once are either uncommon or are highly desirable for agronomic crops and have been cleared of forests. Also, fragipans occurred in only 30 plots, 2 each for Nuttall oak and green ash and none for cottonwood. The presence of a natural pan severely restricted timber growth, yet not one sample cottonwood tree was found growing over a pan. Although this soil factor is very important, its weighty influence was demonstrated for only about half the species included in this study.

When the range of sampled conditions is limited, the soil and site factors measured in the present study are sometimes strongly related to tree growth. For example, on the 15 cherrybark oak plots on Memphis silt loam, growth was closely related to depth of topsoil. All plots were gently sloping. The tallest tree, 118 ft at age 50, was on a plot with 12 inches of topsoil. The shortest, 78 ft at age 50, was on a site with 2 inches of topsoil. The equation,

$$\text{Site index} = 73.6 + 3.64\ (\text{depth of topsoil}),$$

had an r value of 0.88. Thus, 77 percent of the variation in site index was accounted for by depth of topsoil. The standard error of individual estimates was 6 ft. Apparently, many of the determinants of cherrybark oak height growth are approximately equal on Memphis silt loam, at least on the sloping plots examined, and the influence of topsoil is magnified. But the equation has little value because of the small range of conditions to which it applies. Further, it does not help to explain the reasons for most of the variation in site index for cherrybark oak.

Carmean (1967) recently described a refined method for predicting black oak site quality. He related physiography to moisture availability and identified poor and good internal drainage (or aeration) conditions for tree growth, but only in a limited range of soil conditions. He cautioned that "data for this site study were taken from undisturbed forest stands growing on forest soils that were never cleared for grazing or cultivation." It appears that application, then, would be restricted to similar populations, which in some parts of the country are practically nonexistent.

In the present study, the low overall accuracy of preditions from the multiple regressions may be due to the inclusion of factors that are largely effects rather than causes of tree growth. Such factors as organic matter should be used with care in site prediction studies. Occasionally, organic matter content has been shown to have a strong negative correlation with site index. Della-Bianca and Olson (1961) attributed the negative organic matter-site index relationship in their study to thin but highly organic A_1 layers over clays that supported poor oak and pine growth. Although readers were cautioned about application of the prediction equation, the unwary or careless may accept the equation as better than nothing. Because organic matter buildup in this example was a result of tree cover, it should not be used as an indirect indicator of productivity. Where the organic matter of the A_1 horizon is lost in some way, such as by burning, a prediction based on organic matter content will be very poor. Factors that cannot be used to predict site index for open or disturbed land are of doubtful value. Where timber stands are present, site quality can be measured directly and no prediction is needed.

Even where samples are selected and measured carefully, sources of error are abundant. It is impossible to distinguish genetic variations in sample trees from those caused by site factors. Many factors are difficult to measure accurately. A history of high-grading has left mostly ragged, low-grade stands that in no way indicate site quality. Determining exact age from increment cores is a most troublesome source of error, especially on diffuse-porous species such as sweetgum. Scientists experienced in taking such measurements have been known to disagree by several years in the age of a tree.

The present study shows that sites cannot be accurately evaluated for southern hardwood timber production with equations derived over broad areas and complex land patterns. And equations that represent small areas or restricted conditions are of limited value to the land manager. A manager with long experience on a small area should be able to estimate site index from subjective variables that he has observed. Southern hardwood site indexes, for example, are usually estimated by local managers from general topographic features, past history, or soil survey maps and woodland interpretation reports.

The relationships between soil characters and height growth seem to defy quantification. The research problem is confounded by widely varying responses of different species to a single set of conditions. Green ash and Nuttall oak have far different aeration requirements than other southern hardwoods. Cottonwood, sweetgum, and green ash are more responsive than oaks to high moisture availability during the growing season (Broadfoot 1967).

It is generally concluded, therefore, that the soil-factor approach to determining site index has been exploited to a practical limit in this study. Although the procedure has worked well in some upland areas for hardwoods as well as pine, results from the complex alluvial soils of the Midsouth have been discouraging, except when samples were drawn from very small and very uniform areas.

Accurate prediction equations must contain objectively measurable variables that faithfully express soil moisture and nutrient availability during the growing season, physical condition including root growing space, and soil aeration. For southern hardwoods, at least, the purpose of future studies should be to test new expressions of these determinants of productivity.

Past research using the soil factor approach in essence has been only scratching the surface of the problems of site evaluation. It seems a start must be made now to seek the fundamental reasons for measured differences in site quality. When something has been learned about these, researchers will be in a better position to select variables which will lead to models of greater practical value. Whether past research is regarded as applied or fundamental, valuable relationships have been discovered, but the results are essentially negative. Most prediction equations are too imprecise or too restricted in areas of application to be valuable to land managers. The one prime conclusion, therefore, is that more research is needed on basic soil-tree growth relations at the causal rather than the effects level.

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