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Terrain Shape Index: Quantifying Effect of Minor Landforms on Tree Height

W. HENRY MCNAB

ABSTRACT. In the southern Appalachians, the distribution and growth of trees are highly correlated with local topography, but the relationships have been difficult to describe quantitatively. A quantitative expression of the geometric shape of the land surface (terrain shape index) is described and correlated with overstory tree heights and site quality. Application of the index in three even-aged stands of yellow-popular (*Liriodendron tulipifera* L.) on high-quality uniform sites shows that it is highly correlated with total height of trees in a stand, with r^2 ranging from 0.45 to 0.74. In comparisons among stands, the index accounted for an average of 51% of the variation in site index. The relationship was validated in two supplementary stands and accounted for about 49% of variation in site index. The terrain shape index was more accurate in predicting tree height than was lateral shape class, a subjective measure of slope shape occasionally used in soil-site studies. FOR. SCI. 35(1):91–104.

ADDITIONAL KEY WORDS. Site quality, height growth, site index, *Liriodendron tulipifera*.

IN MANY STUDIES IN UNDULATING TERRAIN, height growth of forest trees has been correlated with variables that describe landform. Significant ones have included slope azimuth, slope gradient, position on the slope, length of slope, and geometric shape of the site. The landform variables associated with tree growth, however, have been inconsistent among studies. For example, Doolittle (1957) and Hannah (1968) reported that total height of black oak (*Quercus velutina* Lam.), was correlated with position on the slope but not with shape of the slope. However, Carmean (1967), working with black oak, and Auchmoody and Smith (1979), working with upland oaks, found that tree height was related to both factors. Where surface shape was included in soil-site studies of other eastern hardwoods, it was correlated with total height of white oak (*Quercus alba* L.) (Hannah 1968) but not yellow-poplar (Munn and Vimmerstedt 1980, Brown and Marquard 1988).

Part of the inconsistency among studies may arise from different methods in field measurement. Typically, land surface geometry is described as a discrete variable and sites are grouped into three perceived classes of shape: convex, linear, or concave. Surface shape, however, varies continuously and if expressed as a quantitative variable, it may be found to be more closely and consistently correlated with tree growth.

Little has been reported in the forestry literature on expressing surface shape as an objectively measured, continuous variable. Attempts to describe and quantify the effects of land surface geometry have been made in other disciplines, including geomorphology (Hack and Goodlett 1960), climatology (Grafton and Dickerson 1969), ecology (Callaway[1]), and forestry

The author is Silviculturist, USDA Forest Service, Southeastern Forest Experiment Station, Asheville, N.C. 28804. Two referees provided helpful reviews, as did D. E. Beck, C. E. McGee, J. W. McMinn, and W. T. Swank in an earlier version of the manuscript. Comments and suggestions by H. C. Smith and R. H. Zahner were particularly beneficial. The help of all reviewers is gratefully acknowledged. Manuscript received June 11, 1987.

[1] Callaway, R. M. 1983. Prediction of growth in classified forest stands in the western Great Smoky Mountains National Park. Unpubl. thesis, Univ. Tenn., Knoxville. 110 p.

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(Tajchman 1975). Most of the reported work has concerned mesoscale topography, and none of the proposed techniques have been widely accepted or applied to smaller areas.

The concept of the terrain shape index evolved from a fortuitous combination of events: a premise presented by Hack and Goodlett (1960), a serendipitous field observation, and a suggestion by David L. Loftis.[2] Working in the central Appalachians of Virginia, Hack and Goodlett (1960) suggested viewing the landscape as an irregular matrix of curvilinear geometric shapes and hypothesized that the distribution and basal area stocking of forest vegetation is correlated with the effects of land surface shapes on movement of water. This concept was used to develop a terrain shape index. My index was independently developed but, as was later learned, closely parallels a measure of surface shape reported by Sinai et al. (1981) that was used to study yields of wheat from arid agricultural land in Israel.

This paper describes an index for the quantitative description of surface shape of forest sites. It also reports the relationship of this index to site index within and among stands of yellow-poplar on relatively homogeneous, mountainous locations. Another objective of the study was to compare the index with lateral shape class, a variable that has been used in soil-site studies to account for the effects of surface shape. Yellow-poplar was studied because it is highly responsive to slight changes in site quality (Doolittle 1958, Beck and Della-Bianca 1981), and it occurs in large, generally even-aged stands on moist sites in the southern Appalachians.

METHODS

Hack and Goodlett's (1960) definitions of curvilinear geometric shapes of land surface were simplified by allowing straight lines to approximate the curved surface between a point of reference of the observer and the boundary of the sample site. The concept can be visualized for convex topography by assuming an observer is at the center of a circular plot located on a knoll. The knoll resembles a cone but has different slope gradients in various directions (Figure 1).

Calculating the Index

In essence the index represents the mean relative difference in elevation between the center of a plot and its boundary. Elevation of the observer, Z_0, defines a fixed horizontal reference plane. The plot radius, R, when projected on the cone's surface below the observer, defines a sloping elliptical plane with a boundary ranging between maximum and minimum elevations at points Z_1 and Z_3. The mean difference in elevation between the observer and the plot boundary is:

$$\overline{Z} = ((Z_1 - Z_o) + (Z_2 - Z_o) + \ldots + (Z_n - Z_o))/N \qquad (1)$$

where

$\overline{Z}$ = mean elevation of the plot boundary in reference to the observer

Z_1, Z_2, Z_n = elevations sampled around the plot boundary

Z_o = elevation of the observer

[2] Research Ecologist, Southeastern Forest Experiment Station, Asheville, N.C. Pers. comm., December 1983.

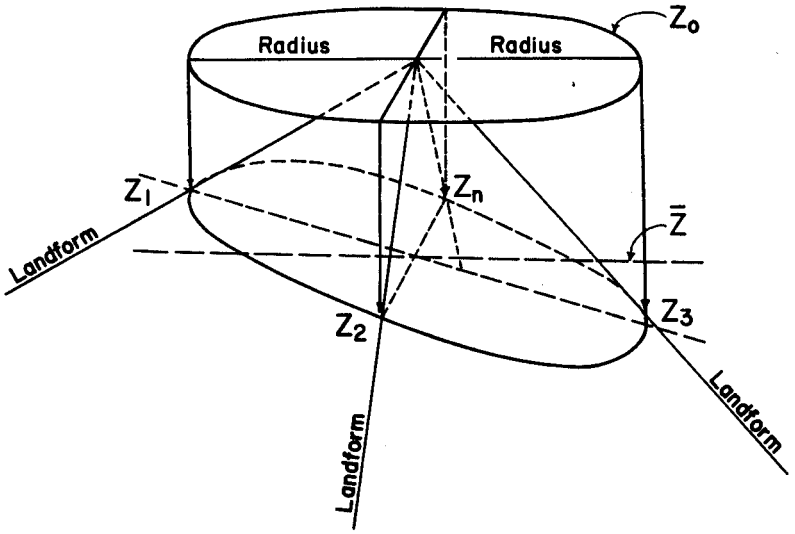

FIGURE 1. Oblique view of sample plot on landform with convex topography. Z_o = horizontal plane of observer; Z = horizontal plane at mean plot elevation; Z_1, Z_2, Z_3, Z_n = elevations sampled around plot boundary.

N = number of points (directions) sampled for elevation.

For convex topography (see Figure 1), the sign of $\bar{Z}$ will be negative because the mean elevation of the plot boundary is less than the elevation of the observer. Similar logic is used in visualizing a plot situated on concave topography, except the value of $\bar{Z}$ will be positive. A value of $\bar{Z}$ near O would indicate a nearly linear, but not necessarily level, surface shape, such as might occur on a side slope.

Although plot size does not enter into determination of $\bar{Z}$, the gradient of surface curvature varies, depending on the size of the area being described. Standardizing the index for plot size yields:

$$\text{Terrain shape index} = (\bar{Z})/R$$

where

$\bar{Z}$ = mean elevation of the sample plot boundary

R = plot radius measured in the units used for elevation.

The terrain shape index is thus equivalent to the mean slope gradient of the plot boundary as viewed from the plot center, with units of meters change in elevation per meter of plot radius.

The terrain shape index has a wide range of possible values, from negative to positive infinity. However, for most applications related to forest vegetation, the terrain shape index will likely range from −1 m/m to +1 m/m. This range of values includes those sites with a mean vertical inclination or declination around the plot boundary of ±45°, or slope gradient of ±100%. For example, typical values of terrain shape index sampled on mountain landforms in the southern Appalachians ranged from −0.24 to −0.12, on convex upper slopes near ridge tops, and from +0.09 to +0.17 on concave lower slopes.

An example illustrates combining equations (1) and (2) for calculation of the index. Assume an observer measures elevations in two directions from the center of an 18 m radius plot which has an elevation of 100 m. Com-

bining Equations (1) and (2) with these data results in a terrain shape index of

$$[(96.4\text{ m} - 100\text{ m}) + (110.8\text{ m} - 100\text{ m})]/[(2)(18\text{ m})] = 0.2\text{ m/m}$$

In practice, calculations are easier and equivalent results are obtained by measuring slope gradients in percent and assuming the observer is at a relative elevation of zero meters.

Sample Stands

Stands in three locations in the Pisgah National Forest of western North Carolina were selected for study; the areas are known as Rocky Bluff, Daniel Ridge, and Long Branch (Table 1). All stands are on lower slope positions of large coves opening to the northeast or southeast and occupy topographic positions with relatively homogeneous rates of evapotranspiration and isolation (Lee and Sypolt 1974). Soils are fine-loamy, mixed, mesic Typic Hapludults; coarse-loamy, mixed, mesic Cumulic Haplumbrepts; or coarse-loamy, mixed, mesic Umbric Dystrochrepts. Stand species compositions were predominantly even-aged yellow-poplar, and none of the stands showed signs of recent disturbance. Other canopy species included northern red oak (*Q. rubra* L.), red maple (*Acer rubrum* L.), and black locust (*Robinia pseudoacacia* L.). The subcanopy consisted mainly of flowering dogwood (*Cornus florida* L.), sourwood (*Oxydendrum arboreum* [L.] DC. and red maple. Mean site index ranged between 48 m and 53 m for yellow-poplar, and all stands appeared fully stocked. The three study locations are widely separated and are 42 km northwest, 37 km southwest, and 16 km south-southwest of Asheville.

Sampling Methods

Intensity of field sampling for calculation of terrain shape index depends on variability of the local topography. A symmetrical surface shape might require a minimum of one measurement, but extremely variable topography requires many measurements. To aid in planning this study, terrain shape index was estimated on 10 circular 0.1 ha plots situated on a variety of landforms typical of mountain topography, ranging from a rounded knoll to a narrow creek bed with steep sides. Relative differences in elevation be-

TABLE 1. Mean and range of arborescent and topographic characteristics of yellow-poplar stands for model development at three locations in the Pisgah National Forest, NC.

Stand and site characteristic	Rocky Bluff	Timber stand Daniel Ridge	Long Branch
Age (yr)	46	76	23
Height (m)	35	37	21
Site index (m)	37	34	35
Basal area (m^2)	13.3	15.2	11.6
Elevation (m)	550	975	915
Aspect (deg)	46 (18,80)	85 (71,79)	49 (28,68)
Gradient (%)	42 (23,61)	56 (38,72)	49 (28,68)
Terrain shape index	0.04 (−0.03,016)	0.02 (−0.13,0.15)	0.02 (−0.07,0.12)
Lateral shape class[a]	0.4 (−1, +1)	0.1 (−1, +1)	0.2 (−1, +1)

Numbers in parentheses indicate range.
[a] Shape code: convex = −1, linear = 0, concave = 1.

tween the plot center and boundary were determined with a hand-held clinometer. Slope gradient was determined to the nearest percent as successive 11.25-degree intervals around the plot perimeter for a total of 32 observations per plot.

Terrain shape index was calculated from the plot data by two methods: (1) ignoring plot topography by always beginning in the north direction, or (2) considering topography by beginning in the aspect direction. Beginning with a single measurement of slope gradient (either in the north or aspect direction), terrain shape index was repetitively estimated six times for each sample plot by doubling the number of opposing directions included in the calculations; i.e., N = 1 = north, N = 2 = north + south, N = 4 = north + south + east + west, etc.; N = 1 = aspect, N = 2 = aspect + 180°, etc.

Thirty 0.1 ha circular plots were established in each of the three study stands. A "subject tree" technique was used for field data collection whereby a single dominant or codominant tree served as the plot center and its growth provided an analog of local environmental conditions, competition, and genetic influence (Opie 1968). Total height of the subject yellow-poplar was estimated to the nearest 0.6 m by using a hand-held clinometer and a variable slope-distance measuring technique. Beck's (1962) curves for yellow-poplar were used to estimate plot site index from total age and height of the subject tree.

Plot size was arbitrarily selected to encompass an area small enough to be utilized by a single tree, yet sufficiently large to represent surrounding topography that could affect growth of the subject tree. Surface shape of the plot around the subject tree was determined by terrain shape index and lateral shape class. Terrain shape index was estimated from percent slope gradient sampled at eight equally spaced directions around the plot boundary. Lateral shape class, as viewed from the plot center, was subjectively described in conventional terms as concave, linear, or convex.

In the experimental design, factors that can influence the growth of yellow-poplar were controlled. Only stands in cove landforms were studied, and sampling within stands was done only on aspects from 0–90° azimuth. Variation in site quality resulting from plot position on the slope was reduced by restricting sampling in each stand to a contour band about 60 to 120 m wide. Plots were only on mid- to lower slopes where deep colluvial soils were present and soils were likely to be moist. Surface shape, however, was intentionally varied by sampling extremes in microscale topography in each stand. Thus, sites within stands would be expected to have similar length of growing season, light regime, and generally uniform soil moisture and other edaphic factors, but they would differ in conditions associated with variable land surface geometry.

Data Analysis

The relationship between height of yellow-poplar and terrain shape index was initially examined by using scatter plotting and correlation analysis, followed by univariate regression analysis. Conditional error tests (Freese 1967) were used to compare linear relationships within and among stands. Two null hypotheses were formulated and tested: (1) height of individual trees within a stand is unrelated to terrain shape index, and, if (1) is rejected, then (2) the relationship of tree heights to terrain shape index is the same for all stands. Tests were performed at the $\alpha = 0.05$ significance level.

For statistical comparisons involving the discrete variable lateral shape

class, the field data were coded: convex = −1, linear = 0, concave = +1. The relationship between lateral shape class and terrain shape index was evaluated using analysis of variance. Regression analysis was used to evaluate the relative value of each estimator of surface shape as a predictor of total-tree height in each of the three study stands. Accuracy of prediction was calculated with the following formula:

$$\text{Accuracy} = \Sigma \mid (H_e - H_a) \mid /N$$

where

H_e = Estimated height of tree (meters)
H_a = Actual height of tree (meters)
N = Number of trees in sample

Field data and statistical analyses were summarized by SAS (Helwig and Council 1979).

RESULTS AND DISCUSSION

FIELD OBSERVATIONS

Results of the two methods and the intensity of field sampling to determine terrain shape index are shown in Figure 2. Estimates of terrain shape index almost always stabilized when four directions were sampled and changed little after measurements in eight or more directions. Calculation of terrain shape index based on measurement in four directions should be adequate for most purposes.

Method of calculation had little effect on rate of stabilization of terrain shape index. However, mean estimates were more uniform with fewer measures of elevation when beginning in the north direction because it tended to provide a random starting point. In contrast, measurements beginning in the aspect direction were always initially biased below the final value of terrain shape index.

RELATIONSHIP OF THE INDEX TO HEIGHT

Within-Stand Variation

Scatter plotting of the field data indicated that total-tree height of yellow-poplar was directly related to terrain shape index in each of the three study stands (Figure 3). Correlations were lowest for the Rocky Bluff site and highest for Daniel Ridge. A linear regression model

$$\text{Total height (m)} = b_o + b_1 \text{ (terrain shape index)} \qquad (3)$$

was used to determine the relationship of height to terrain shape index. The coefficients for terrain shape index were highly significant ($P < 0.01$) for each of the three study stands. Examination of the plotted residuals of the regression lines indicated that a linear model was appropriate for each stand. The null hypothesis that tree heights are unrelated to terrain shape index was rejected.

Yellow-poplar height varied widely in each of the three study stands, even though the areas sampled were small and occupied sites with what appeared to be relatively homogeneous environmental conditions. A portion of this

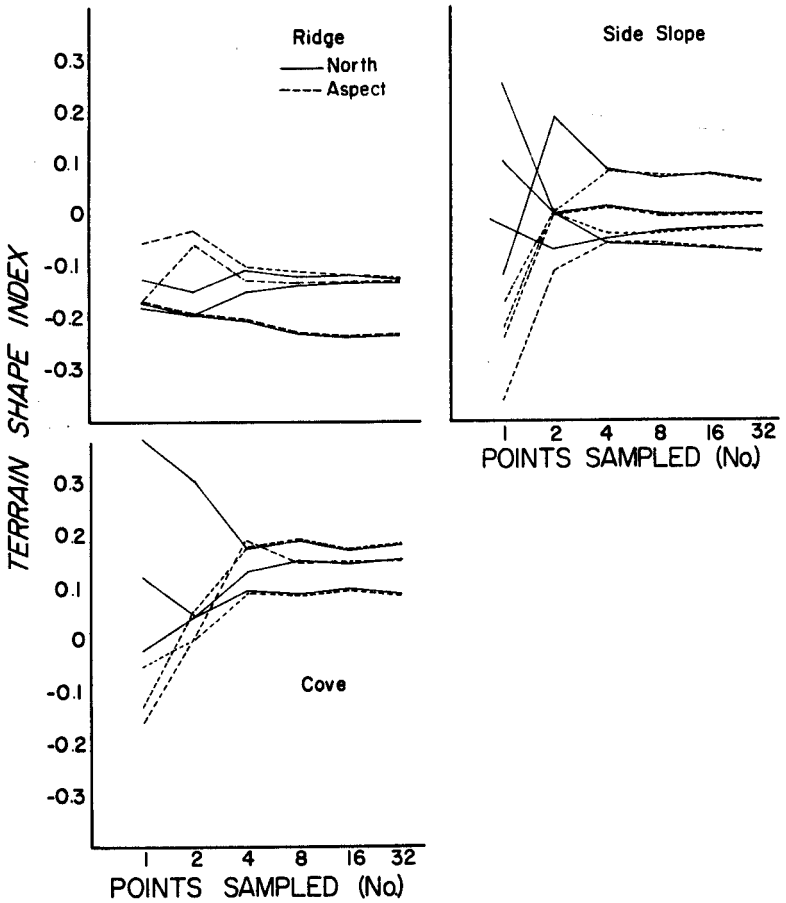

FIGURE 2. Relation of terrain shape index to number of directions measured on 0.10 ha plots by two methods of computation: (1) beginning in north direction and (2) beginning in aspect direction, and in both cases successively doubling number of directions in a symmetrical pattern. Three plots were on ridges, four on side slopes, and three in coves, typical landforms of mountain topography.

variation is evidently attributable to local variation in topography immediately around each subject tree. Other sources of unmeasured variation contributing to differences in height include genetic variability, current competition among neighbors, and differential rates of juvenile height growth associated with origin as a seedling or sprout.

Among Stand Variation

The hypothesis that response of yellow-poplar height growth to terrain shape is similar among stands of the same age was also tested. After using site index to adjust ages and heights of the three study stands to 50 years, the field data were plotted against terrain shape index. The relationship between site index and terrain shape index appeared linear for each stand. Using site index as the dependent variable, univariate regressions of the form

$$\text{Site index} = b_o + b_1 \text{ (terrain shape index)} \quad (4)$$

were fitted to the data of each stand and resulted in regression coefficients

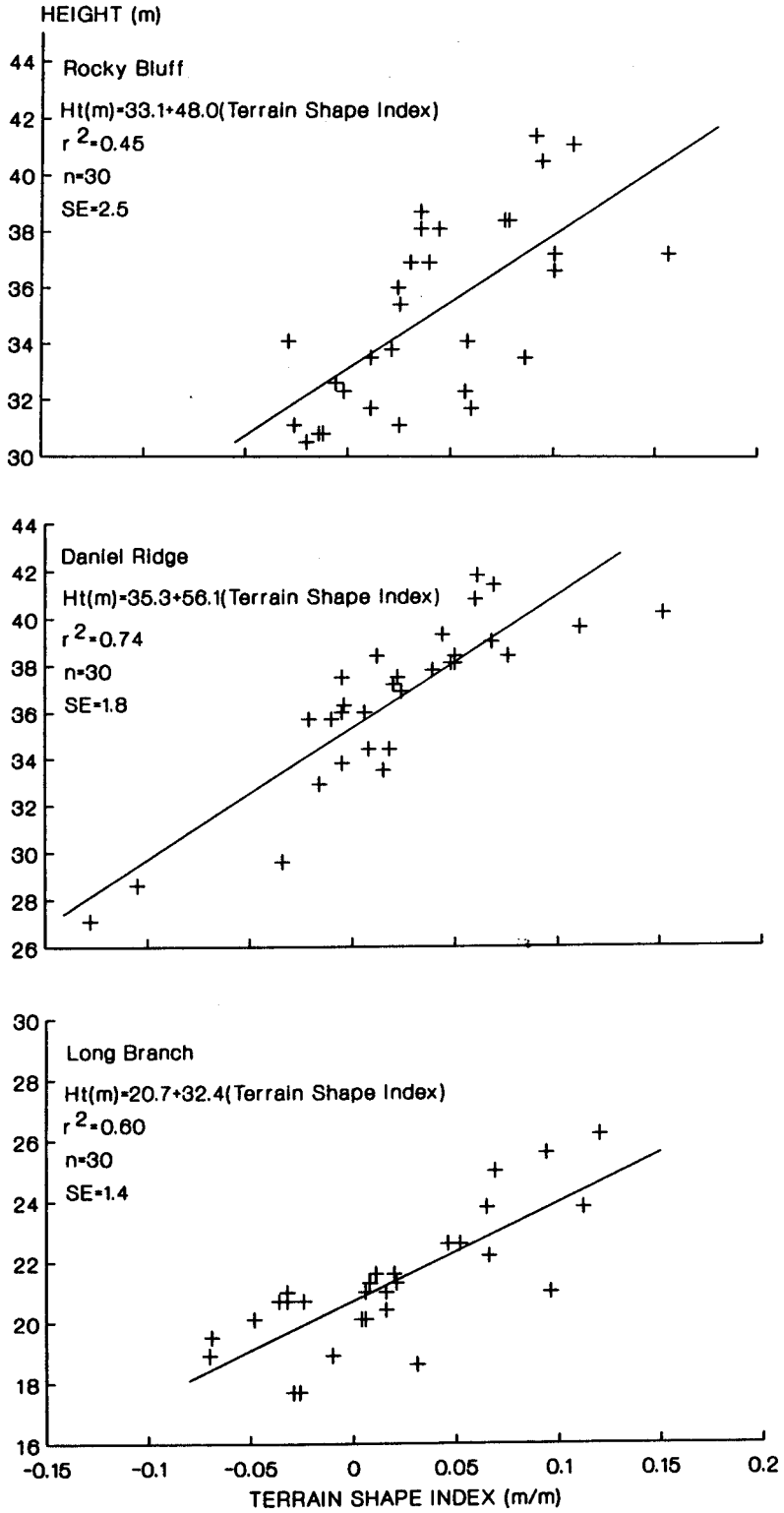

FIGURE 3. Relationship of three height and terrain shape index for even-aged stands of yellow-poplar at three locations on the Pisgah National Forest.

of similar magnitude (Figure 4). An F-test of conditional error revealed no significant differences in the slope parameter of the three study stands. The intercept of the Daniel Ridge equation was significantly different from the intercept of equations for the Rocky Bluff and Long Branch stands. The cove formed by Daniel Ridge opened to the southeast, compared with northeast aspects for the other two cove locations. Difference in aspect could have contributed to a slightly lower mean site quality for Daniel Ridge (Hack and Goodlett 1960). These results suggest that the response of yellow-poplar height growth to terrain shape was the same at each location even though the overall level of stand site quality differed slightly.

Although these data were collected primarily for the purpose of evaluating the utility of the terrain shape index in measuring land surface geometry, the results also suggest that yellow-poplar in this geographic area has a predictable height response to land surface configuration. The data were pooled and a simple linear regression that used equation (4) was fitted to the 90 observations. The regression model was highly significant ($P < 0.01$) and accounted for about one-half of the variation in site index among the study stands (Figure 4). If the relationship of tree height and terrain shape index is consistent, it would be a useful independent variable in soil-site relationships.

Validation of Relationship

The pooled regression model was tested for validity in yellow-poplar stands at two other locations: Laurel Cove, in the Bent Creek Experimental Forest, and Rocky Fork, in the Pisgah National Forest. Laurel Cove is about 2.4 km north of Long Branch, at a slightly higher elevation. Rocky Fork is about midway between the Daniel Ridge and Long Branch stands, and consists of a complex drainage pattern of several small coves sur-

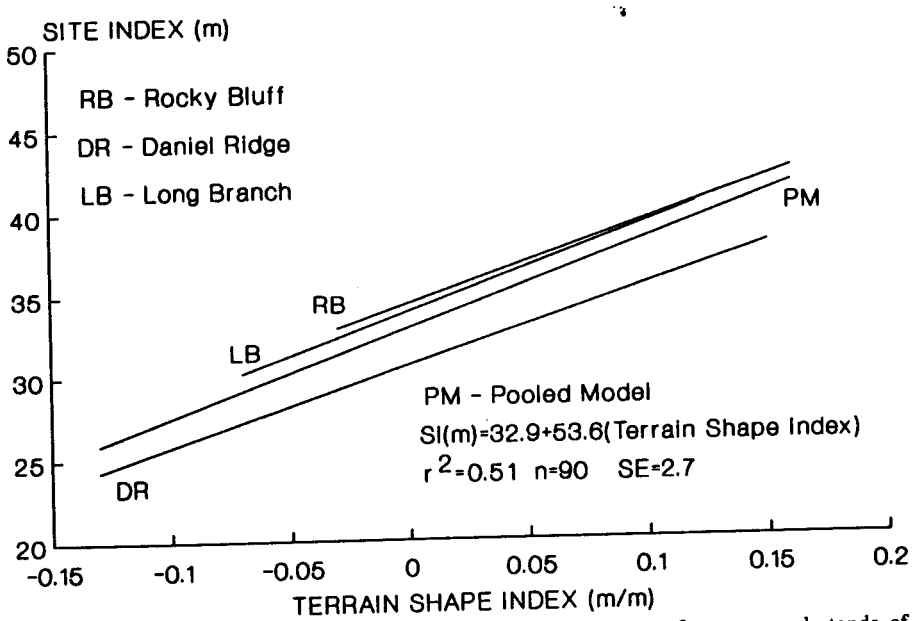

FIGURE 4. The relationship of site index and terrain shape index for even-aged stands of yellow-poplar, and for the pooled data.

rounded on three sides by higher landforms. Both coves open to the northeast, are larger than the three coves containing the study stands, and contain a slightly broader range of yellow-poplar site and stand conditions than were sampled in the study stands.

A series of 0.1 ha plots had been previously installed in each cove as part of a long-term study of growth and yield.[3] Mean plot age had been determined in 1965 and all trees had been numbered and measured for total height at that time. Sampling methods for the model validation were similar to those used in the three study stands, with several minor exceptions. Some of the original sample trees in each plot were selected as subject trees for determination of terrain shape index. Site index had been estimated in 1965, but terrain shape index was based on current conditions. Characteristics of the two validation stands are given in Table 2. Tree ages varied among plots in the validation stands, most likely because of the pattern and timing of past land use. Mean site index in Della-Bianca's study (see footnote 3) was 22 m at Laurel Cove and 35 m at Rocky Fork.

Site index for 21 subject trees in Laurel Cove and 36 subject trees in Rocky Fork Cove was regressed as a function of terrain shape index and plotted, Figure 5. All but three of the predicted site indexes are within the 95% confidence limits delineated for individual estimates using the pooled model for among-study stands. Predictions from both validation stands are well distributed, although variation is greater for the Rocky Fork location than for Laurel Cove. Rocky Fork Cove is larger than Laurel Cove and variation in slope positions of the plot locations is greater.

Data from the validation stands were also subjected to regression analysis and the coefficients compared with those from the pooled model. No significant departure from homogeneity of the coefficients for terrain shape index were revealed by conditional error tests. However, the intercept of the regression for Laurel Cove was significantly less than the intercept of the pooled model. These results suggest that the effect of terrain shape on site index of yellow-poplar was about the same for the three pooled study stands and the two validation stands, even though mean site quality varied slightly.

TABLE 2. Mean and range of arborescent and topographic characteristics of yellow-poplar stands for model validation at two locations in the Pisgah National Forest, NC.

Characteristic	Laurel Cove	Rocky Fork
Sample plots (no.)	5	8
Subject trees (no.)	21	36
Arborescent		
Age (yr)	62 (55,69)	43 (34,61)
Height (m)	33 (30,38)	30 (23,36)
Site Index (m)	31 (27,35)	33 (25,40)
Topographic		
Elevation (m)	915	854
Aspect (deg)	60 (13,89)	60 (0,92)
Gradient (%)	41 (32,52)	35 (12,60)
Terrain shape index (m/m)	0.0 (−0.5,0.07)	0.0 (−0.06,0.10)

Numbers in parentheses indicate range.

[3] Della-Bianca, Lino. 1965. A study of the effects of stand density upon growth and yield of pure yellow-poplar in the southern Appalachian Mountains. Establishment and Progress Report on file at Bent Creek Experimental Forest. Asheville, NC.

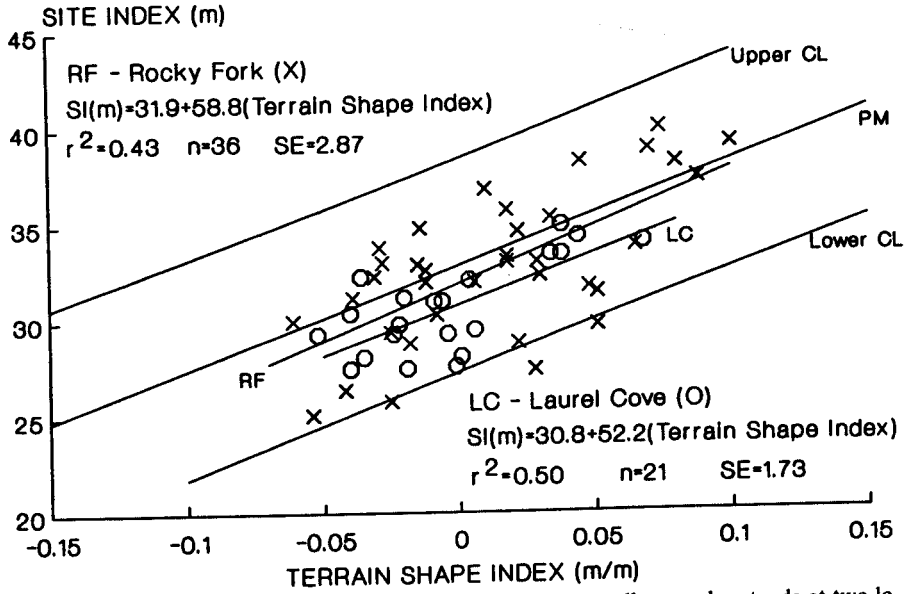

FIGURE 5. The relationship between predicted site index for yellow-poplar stands at two locations sampled for validation of the pooled model (PM). Upper and lower confidence limits (CL) are shown at the 95% level.

Comparison with Lateral Shape Class

Analysis of variance indicated that terrain shape index was significantly related to lateral shape class for the three study stands. These results suggest that terrain shape index quantified land surface geometry of the sample plot as perceived by the observer.

Regression analysis indicated that terrain shape index is a better predictor of tree height than lateral shape class (Table 3). The accuracies of prediction were greater for the terrain shape index than for lateral shape class in each of the three study stands. Mean absolute deviations of the terrain shape index ranged from 4 to 6% of average total stand height.

Relationship with Biological Processes

Because I did not measure site environmental factors, biological explanations for my observations of variation in tree height must be inferred from results of other studies. Yellow-poplar is a mesophytic species that responds in height growth mainly to physical properties that affect the capacity of the

TABLE 3. Accuracy of estimates of terrain shape index and lateral shape class for predicting total height of yellow-poplar trees in three even aged stands in the Pisgah National Forest, NC.

Stand	Average height	Terrain shape index	Lateral shape class
	m	..... (m)	
Rocky Branch	35	2.1	2.2
Daniel Ridge	36	1.4	2.2
Long Branch	21	1.1	1.4

Estimated accuracy is the mean absolute deviation.

soil to supply moisture and somewhat to soil chemical properties (Beck and Della-Bianca 1981). Results from several plantation studies illustrate the often marked differences in yellow-poplar height growth in response to these soil properties. Working in a 0.85 ha stand, Gilmore et al. (1968) observed that total height of 18-year-old trees, which ranged from 3 to 18 m, was highly correlated with depth of organic matter incorporated in the soil and also found that considerably more leaf litter was present on high-quality sites than on low sites. Schomaker and Randolph (1964) found that 24-year-old trees bordering a mixed-species hardwood stand were twice as tall as those in other areas of the plantation, and concluded that decomposition of hardwood leaf litter that had blown into the yellow-poplar stand benefited height growth by improving soil physical properties and increasing the soil nutrient status. Litter is an important factor that affects site quality in deciduous forests, and as Stone (1977) points out, "Leaf redistribution may have significant ecological effects, particularly in mixed stands composed of species that cycle nutrients at various rates."

Several studies have dealt with the relationship between litter and microtopography in forest stands. In northern hardwood forests, the wind-caused redeposition of forest litter significantly increased soil N, Ca, and Mg supplies in depressions (Welbourn et al. 1981). Working on mound-and-depression microtopography in another northern hardwood forest, Hart et al. (1962) reported that litter was three to five times deeper, and humus was three to four times thicker in concave than in convex areas of the forest floor. Results from a study by Dwyer and Merriam (1981) revealed that soil organic matter content was consistently greater on low topographic sites than on level or high sites and soil temperature varied less in depressions, providing a more favorable environment for bacteria and other decomposers. Also, moisture content is generally greater in concave soil surfaces compared to adjacent convex shaped areas (Dwyer and Merriam 1981, and Sinai et al. 1981).

The results of this study suggest that differential rates of litter accumulation and decomposition, and its subsequent effects on soil physical properties, may be a contributing cause of the differences in growth of yellow-poplar on microsites with various land surface shapes. The beneficial effects of leaf litter accumulation and decomposition, combined with gravitational movement of subsurface water on mountain slopes (Hewlett and Hibbert 1963), creates microsites of higher site quality for yellow-poplar in depressions compared with adjacent convex mounds. Results of this study also suggest that minor landforms may be a more important source of areal site variation within stands in the southern Appalachians than previously recognized, at least for a site-sensitive species such as yellow-poplar. Additional study is needed to determine the physical and biological soil properties associated with variable land surface shapes, their relationship to the atmospheric environment, and the response of forest vegetation to these site factors.

Results from this study have several important implications for forest management, particularly the direct estimation of average site quality and delineation of areal units of homogeneous productivity. In this study individual dominant and codominant yellow-poplars in three, 5 ha stands on apparently uniform sites, varied by up to 10 m in height. When site index is used to evaluate site quality, careful consideration must be given to sample-tree selection to fully represent microtopography in the stand. In addition, average stand sizes must be small and closely associated with landform to

avoid excessive variation in site quality caused by heterogeneous topography. Terrain shape index objectively relates height growth of a species to land surface shape for evaluation of site productivity.

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