A topographic index to quantify the effect of mesoscale landform on site productivity

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Landform is related to environmental factors that affect site productivity in mountainous areas. I devised a simple index of landform and tested this index as a predictor of site index in the Blue Ridge physiographic province. The landform index is the mean of eight slope gradients from plot center to skyline. A preliminary test indicated that the index was significantly associated with slope position and three classes of landform (ridge, slope, and cove). In a test with data from four locations, site index of yellow-poplar (*Liriodendron tulipifera* L.) was significantly correlated with landform index for each location (r = 0.45-0.65). Landform index and two other topographic variables together accounted for 31 percent of the variation in yellow-poplar site index throughout the Blue Ridge province. Landform index is a conveniently measured site variable that may be useful in various forestty-related applications, including multivariate analysis of the distribution and composition of forest vegetation.

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Les formes de paysage sont interreliées aux facteurs environnementaux qui influencent la productivité stationnelle en zone montagneuse. Un indice simple pour les formes de paysage a été développé et mis à l'essai comme estimateur de l'indice de fertilité dans la province physiographique du Blue Ridge. Cet indice de la forme de paysage est la moyenne de la force de la pente de huit segments allant du centre de la placette à la ligne de crête. Un test préliminaire indiquait que cet indice était associé significativement à la position sur la pente et trois classes de forme de paysage (crete, versant et cuvette). Dans un test qui utilisait les données provenant de quatre emplacements, l'indice de fertilité du tulipier (*Liriodendron tulipifera* L.) était significativement corrélé avec l'indice de forme de paysage pour chaque emplacement (r = 0,45–0,65). L'indice de forme de paysage et deux autres variables topographiques expliquaient ensemble 31% de la variation de l'indice de fertilité du tulipier dans la province du Blue Ridge. L'indice de forme de paysage est une variable stationnelle facilement mesurée qui peut être utile pour diverses applications forestières, y compris pour les analyses multivariées de la distribution et de la composition de la végétation forestière.

[Traduit par la rédaction]

Introduction

Landform significantly affects site productivity and distribution of forest tree species (Rowe and Sheard 1981; Barnes et al. 1982; Bailey 1988). "Landform" can be defined in several ways. A widely used definition is "any physical, recognizable form or feature of the Earth's surface having a characteristic shape and produced by natural causes" (Soil Conservation Service 1986). "Landform" is often used as a geomorphological term. When glaciated areas are described, the term often refers both to surface forms or features and to the origin and geologic material of the features (Rowe and Sheard 1981). In this paper I use "landform" to refer to characteristic shapes of land masses. Landform influences many environmental characteristics, including distribution of precipitation through concentration or dispersal of subsurface water (Helvey et al. 1972), physical propet-ties of soils (Hack and Goodlett 1960), and the atmospheric environment near the ground (Geiger 1965). Moreover, soil–site studies in the Appalachian Mountains show that landform strongly influences height growth of oaks (*Quercus* spp.) (Auchmoody and Smith 1979), pines (*Pinus* spp.), and yellow-poplar (*Liriodendron tulipifera* L.) (Ike and Huppuch 1968). Landform is also an important component in ecological approaches to land classification (Rowe and Sheard 1981; Barnes et al. 1982).

A number of studies have shown the influence of landform on growth, composition, and distribution of tree communities. However, relatively little has been written about the development of field methods for quantifying landforms. In an early soil–site study Auten (1945) reported that yellow-poplar growth was affected by landform when sites were classified as coves, slopes, or ridges. Auten further chatacterized landforms as sheltered or open but offered the user little help in applying his findings. Slope position is often used to account for environmental effects associated with landform, such as differences in soil moisture (Helvey et al. 1972). However, it can be difficult to determine slope position in the field, especially in the southern Appalachians and other regions where complexly dissected landscapes seldom provide definite starting and ending points.

In a few studies involving measurement of environmental variables, researchers reported objective methods of measuring characteristics of landmasses in the vicinity of field plots. Lee and Baumgartner (1966) quantified effects of local relief on topographic shading by determining the mean vertical angle to the topographic horizon in the directions of sunrise and sunset. Grafton and Dickerson (1969) developed an exposure index as a measure of the effect of landmasses surrounding weather stations in mountainous terrain by summing the azimuths where landforms higher than the site were present. Geiger (1965) noted that German climatologists developed instruments to measure "different degrees of obstruction of horizon" that could affect their weather data. In a study of solar radiation and forest site quality, Lee and Sypolt (1974) computed a view factor, which they defined as "the portion of the celestial hemisphere obscured by the slope." However, none of these researchers related site productivity to measures of the horizon.

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TABLE 1. Changes in landform index with increasing numbers of gradient measurements per plot for 10 randomly selected plots on various landforms in Bent Creek Experimental Forest

		Number of measurements					
Plot	Landform	1	2	4	8	16	32
1	Valley	0.030	0.260	0.240	0.251	0.248	0.250
2	Ridge	0.030	0.255	0.170	0.159	0.160	0.162
3	Valley	0.000	0.220	0.230	0.224	0.222	0.222
4	Slope	-0.010	0.180	0.158	0.164	0.164	0.163
5	Slope	0.030	0.160	0.150	0.148	0.148	0.147
6	Valley	-0.010	0.300	0.310	0.274	0.280	0.281
7	Slope	0.140	0.160	0.148	0.146	0.144	0.142
8	Slope	0.150	0.180	0.188	0.166	0.165	0.165
9	Saddle	-0.010	-0.005	0.162	0.166	0.161	0.161
10	Ridge	0.050	0.095	0.082	0.078	0.081	0.082
Mean		0.040	0.180	0.184	0.178	0.177	0.178

In this paper, 1 report a field method for quantifying mesoscale landform: landform of areas larger than microscale sites and smaller than macroscale landscapes (Bailey 1988). The index is based partly on my previous work (McNab 1989) and on a map-derived "exposure index" reported by Callaway (1983), which was highly correlated with forest cubic volume production in the Great Smoky Mountains National Park. Callaway's index seems to be based on a measure of "exposure" developed by Rodriguez (1973), Berglund (1964), Davis (1966), and Lewis (1967). The field method 1 present here is similar to the one apparently developed initially by Berglund (1964) for measuring "shade angle" (the vertical angle from plot center to the horizon at azimuths of S85°E and S85°W).

The main objective of the study reported here was to evaluate the landform index as an independent variable for use in modeling tree growth. Three specific questions were addressed: (i) Is the index associated with conventional measures of landform? (*ii*) 1s the index correlated with site index? and (*iii*) How important is the index as an independent variable in soil–site prediction models?

Methods

Determining landform index

The index is based on landscape features that confine our view of the horizon. For example, in large concave landforms (valleys, hollows, and coves) our view is blocked by adjacent landmasses and we must look up to see the horizon. When we stand on convex and leve1 landforms (ridges and plateaus) the horizon seems to be at eye level. On sloping, planar landforms (slopes and terraces) the horizon is usually above us in one direction and about on our leve1 in the opposite direction. The view of the horizon, in relation to our position on the landform, forms the basis of the landform index.

Determination and computation of the index are simple. A handheld clinometer can be used to measure the gradient, in percent, from the plot center to the horizon. The landform index is the average vertical gradient to the topographic horizon, divided by 100 to convert percent to a decimal value.’ In this instance the horizon is slightly below eye leve1 (-1%) in the direction of aspect and above the horizontal view in the other three directions. If the observer is facing downslope, there are ridges to the observer's right (24%) and left (29%), and a higher ridge (42%) behind the observer. Averaging these four measurements, the landform index would be calculated as

$$[1]\quad \text{Landform index} = \frac{(-1 + 24 + 42 + 29)}{(4 \times 100)} = 0.235$$

This value of the index suggests a moderately concave landform, such as a broad, shallow cove. The index is dimensionless and the effects of height and distance to the landform are compensating factors. For example, the presence of a low, nearby ridge and the presence of a high, distant ridge could have the same effect on landform index. The ecological influences of these landforms could differ, of course.

Landform index can be calculated based on measurement of gradient to the horizon in one or more directions, depending on topographic variability and accuracy requirements. In the southem Appalachian Mountains, 1 have found it satisfactory to calculate the index based on measurements in eight directions per plot. When the first measurement was in the aspect direction (for convenience and reference), estimates of landform index almost always stabilized when gradients were sampled in four directions separated by equal horizontal angles and changed little after measurements were made in eight or more directions (Table 1). In the present study, landform indexes were obtained by measuring slope gradients (with a handheld clinometer) from plot centers to the horizon in eight directions (in the aspect direction and at 45” intervals). Gradient was measured to the nearest 1 percent.

Preliminar-y comparison with conventional measures

1 made a preliminary study of the relationship between landform index and slope position at the Bent Creek Experimental Forest in western North Carolina (35.5°N, 82.6°W). Data were collected on four typical slopes along transects extending from ridge top to valley bottom (Table 2). 1 first determined the total length of each slope by pacing and then employed the methods already described to measure landform index at the 0 percent slope position (ridge) and at 10 percent intervals to the bottom of the valley. Landform index was directly correlated (mean $r = 0.97$) with slope position along each transect and approximately doubled in magnitude from ridge to valley. Values of landform index varied somewhat among transects depending on characteristics of the slope and surrounding topography.

A second preliminary study investigated the relationship between the landform index and conventional, qualitative descriptions of landforms at the Bent Creek Experimental Forest. Data were collected at 152 randomly located sites within an area of approximately 1000 ha, over a wide range of topographic conditions. I recorded three classes of landform:

(1) Ridge, a long, narrow elevation of the land surface, usually sharp crested with steep sides and forming an extended upland between valleys.

‘Decimal conversion of the landform index is unnecessary for most field applications, but this conversion is helpful in geographic information system applications.

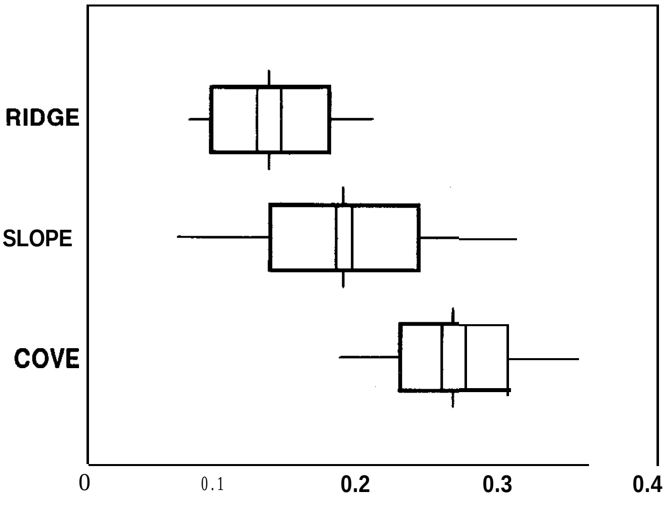

FIG. 1. Mean (vertical lines), range (horizontal lines), standard deviation (horizontal bars), and standard error (vertical bars) of landform index associated with three classes of landform in Bent Creek Experimental Forest.

TABLE 2. Association of landform index with slope position along four transects in Bent Creek Experimental Forest

Slope position (%)	Transect*			
	1	2	3	4
0 (ridge)	0.049	0.116	0.151	0.118
10	0.043	0.124	0.155	0.131
20	0.061	0.133	0.159	0.174
30	0.065	0.156	0.164	0.193
40	0.069	0.168	0.181	0.199
50	0.076	0.180	0.191	0.211
60	0.084	0.180	0.204	0.224
70	0.088	0.201	0.211	0.233
80	0.093	0.218	0.233	0.238
90	0.095	0.243	0.256	0.250
100 (valley)	0.099	0.290	0.274	0.268

*Transect lengths and average gradients: (1) 800 m, 6%; (2) 200 m, 20%; (3) 350 m, 10%; (4) 600 m, 17%.

(2) Slope, the slope bounding a drainageway and lying between the drainageway and the adjacent interfluve. It is generally linear along the slope width and overland flow is parallel down the slope.

(3) Cove, a term used in the Appalachian Mountains for a smooth-floored, somewhat oval "valley" sheltered by hills or mountains.

I classified 66% of sample plots as occurring on slopes, 20% as occurring on ridges, and 14% as occurring in coves. Landform indexes for individual plots ranged from 0.070 to 0.355. Mean landform index was lowest for ridges (0.136) and highest for coves (0.267) (Fig. 1). Landform indexes of slopes overlapped those of ridges and coves, which suggests that the averaging process used in the index calculations probably does not follow the decision process the observer employs when classifying landforms. Analysis of variance revealed that landform class accounted for a significant (p = 0.01) proportion of variation in landform index (Table 3).

Results of these two preliminary trials indicated that the landform index was associated with conventional methods of describing landforms in a small geographic area. I designed a larger, more rigorous test to determine whether landform index was also correlated with site quality. Site index for yellow-poplar was used as the measure of site quality because the species is highly responsive to small changes in site conditions (Doolittle 1958).

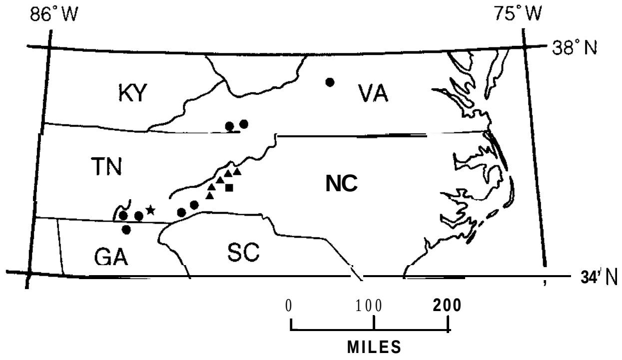

FIG. 2. Location of the four study areas in the southeastern United States. (■) Bent Creek; (★) Nantahala Mountains; (▲) Bald Mountains; (●) southern Appalachians. (1 mile = 1.6 km).

TABLE 3. Analysis of variance of landform index measured on three classes of landform in Bent Creek Experimental Forest

Source	df	Mean square	F-ratio	p-value
Landform class	2	0.10579	43.01	<0.0001
Error	149	0.00246		

Study sites

The study of site quality was conducted in the southern part of the Blue Ridge physiographic province in the southeastern United States. The Blue Ridge province, a long and relatively narrow band of highly weathered mountains, ranges in elevation from 330 to 2200 m, and includes the highest peaks in the eastern United States. The province's climate is characterized by long, warm summers and short, cool winters. Average temperatures at elevations of 760 m are relatively uniform throughout the province, ranging from 1°C in January to 24°C in July. Annual precipitation varies more than temperature, ranging from approximately 100 cm in Virginia to over 200 cm in small areas near the Blue Ridge escarpment in western North Carolina (Donley and Mitchell 1939). Approximately half of the annual precipitation occurs during the growing season.

The province exhibits strongly dissected topography and has a geologic substrate of predominately metamorphic crystalline formations of the Precambrian Era. These formations have been faulted and folded complexly, and are highly weathered. Soils are mainly Ultisols on ridges and moderate slopes and Inceptisols on steep slopes and in coves. Dominant tree cover is deciduous hardwoods consisting mainly of species of *Quercus* on dry slopes and ridges, and a host of mesophytic species such as yellow-poplar on moist slopes and in coves.

In this study, I used four groups of field plots in yellow-poplar stands throughout the Blue Ridge province (Fig. 2). All plots had previously been part of other research studies involving yellow-poplar, but were suitable for two reasons: (i) the plots were located without regard for landform over a broad geographic area and (*ii*) *the* labor-intensive work of finding suitable stands and accurately determining site index (total tree height at age 50 years) had been done by others. Plots were sometimes located in clusters of three to five, to take advantage of suitable areas in available stands. Two groups

TABLE 4. Site index and topographic variables by study location

Variable	Bent Creek	Nantahala Mountains	Bald Mountains	Southern Appalachians
Site index (m)	31.1 (3.0)	33.2 (1.8)	36.6 (2.2)	33.5 (3.8)
Elevation (m)	813 (78)	858 (92)	874 (197)	850 (114)
Gradient (%)	30 (15)	24 (8)	31 (13)	29 (12)
Slope position (%)	58 (32)	45 (10)	80 (18)	72 (30)
Terrain shape index	0.03 (0.05)	0.03 (0.06)	0.12 (0.08)	0.04 (0.05)
Landform index	0.23 (0.05)	0.24 (0.06)	0.32 (0.09)	0.28 (0.06)

NOTE: Values are means with standard deviations in parentheses.

were in small, intensively sampled areas with minimal climatic and geologic variation. Plots in the other two groups were distributed over larger areas in which environmental variation was greater.

Sample plots were located in fully stocked stands that had not been disturbed recently and that showed no stem or crown damage resulting from ice storms, insects, or fire. All plots were 0.25 acre (about 0.1 ha). Approximately half of the plots were selected as part of a study concemed with growth and yield of yellow-poplar (Beck and Della-Bianca 1972) and sampled a range of site indexes (22.5-42.1 m). The other plots were chosen to investigate the influence of geologic substrate and soil properties on yellow-poplar productivity; these plots also sampled a wide range of site indexes. The five tallest trees were selected for measurement in each plot. Tree ages were determined from increment cores, and stands were accepted for plot location if variation in tree age was 3 years or less. Tree total height had been measured with hand-held clinometers. Site index (base age 50 years) for yellow-poplar was determined using height and age relationships developed by Beck (1962).

Intensively sampled areas

Thirty-four plots were located in Bent Creek Experimental Forest (35.5°N, 82.6°W). All of these plots were situated on a 6.4-km section of a prominent ridge paralleling a third-order drainage basin. Annual precipitation at Bent Creek averages 117 cm and the substrate is muscovite-biotite gneiss.

Twenty-four plots were situated in the Nantahala Mountains of western North Carolina (35.1°N, 83.5°W) in a zone of relatively high precipitation (>200 cm/year). Plots were located over a distance of about 10 km, in four first to third order drainage basins. The geologic substrate in the area is predominantly biotite gneiss with inclusions of amphibolites.

Extensively sampled areas

Sixty plots were located in 11 stands in an 80-km section of the Bald Mountains of North Carolina (35.8°N, 83.0°W to 36.1°N, 82.7°W). Although this area is in the Blue Ridge province, it is near the transition zone with the Ridge and Valley province, a region characterized by sedimentary geologic formations. Geologic substrate is variable and consists of intermixed metagranites and gneisses of the Middle Proterozoic Era and metasedimentary rock units of the Late Proterozoic Era. Approximately 2/3 of the plots were situated on soils derived from metasedimentary formations. Topographic conditions here are more varied than they were at other locations. Features not encountered at other locations include narrow V-shaped ravines with steep slopes (>80%); these occur in the metasedimentary formations. Estimated annual precipitation ranges from 119 to 160 cm, varying with elevation (Donley and Mitchell 1939).

Sixty-four plots were located throughout the southern Appalachian region, in a 480-km zone extending from northeast Georgia (34.9°N, 83.7°W) to mid-Virginia (37.8°N, 79.4°W). The southern Appalachian plots were in seven clusters of 2 to 17 plots. Estimated annual precipitation ranges from 160 cm in northem Georgia to 119 cm in central Virginia. Geologic formations are variable, but gneisses and schists predominate.

Field data, main experiment

Mean site index was determined previously, when the plots were established as part of other studies. I determined the following site variables for each plot: landform class, elevation (m), aspect (degrees), slope gradient (percent), slope position (percent), terrain shape index, and landform index. Most of the site variables I recorded are commonly used in studies of soil–site relationships (Carmean 1975). Landform class of each plot was subjectively determined as ridge, slope, or cove. Elevations were determined from 1 : 24 000 topographic maps. Slope position was estimated in the field as the relative distance from the ridge (0%) to the valley floor (100%). Terrain shape index, the mean of slope gradients from plot center to boundary in eight directions separated by horizontal angles of 45" (McNab 1989), was used to quantify surface shape (convexity or concavity) of the sample site. Landform index was measured as previously described.

Distribution of plots by site productivity and topographic characteristics was relatively uniform for all locations other than the Bald Mountains (Table 4). There, mean site index and all other site characteristics except gradient were greater than for the other locations. Over all locations, 96% of plots were equally divided between slopes and coves. Approximately half of the 182 plots were on sites with northeast aspects.

Data analysis

The relationship between site index and landform index at each location was determined by the simple linear regression model:

$$[2]\quad \text{Site index (m)} = B_0 + B_1 \text{ (landform index)}$$

where B_0 and B_1 are regression coefficients.

Field data were plotted so that I could detect possible outliers and determine the general form of the relationship between site index and landform index. Coefficients of the model parameters were determined by regression analysis. Dummy variables were used to account for the effects of different levels of landform class on site index (Afifi and Clark 1990).

Correlation analysis was used to determine the relative values of the landform index and the other measured topographic variables as predictors of site index. SAS procedures (SAS Institute Inc. 1985) were used for all data summaries and analyses. I used site index, instead of tree height, as the dependent variable in order to obtain a better estimate of the relationship between landform index and site quality (Carmean 1975). Normality of site index sample data from the four locations was confirmed using the Kolmogorov *D* and Shapiro and Wilk *W* statistics.

Results and discussion

Association of landform index with site index

There was a direct relationship between site index and landform index at each location (Figs. 3A–3D), with correlation coefficients ranging from 0.45 to 0.65. Relationships at both restricted locations (Figs. 3A and 3B) were strongly

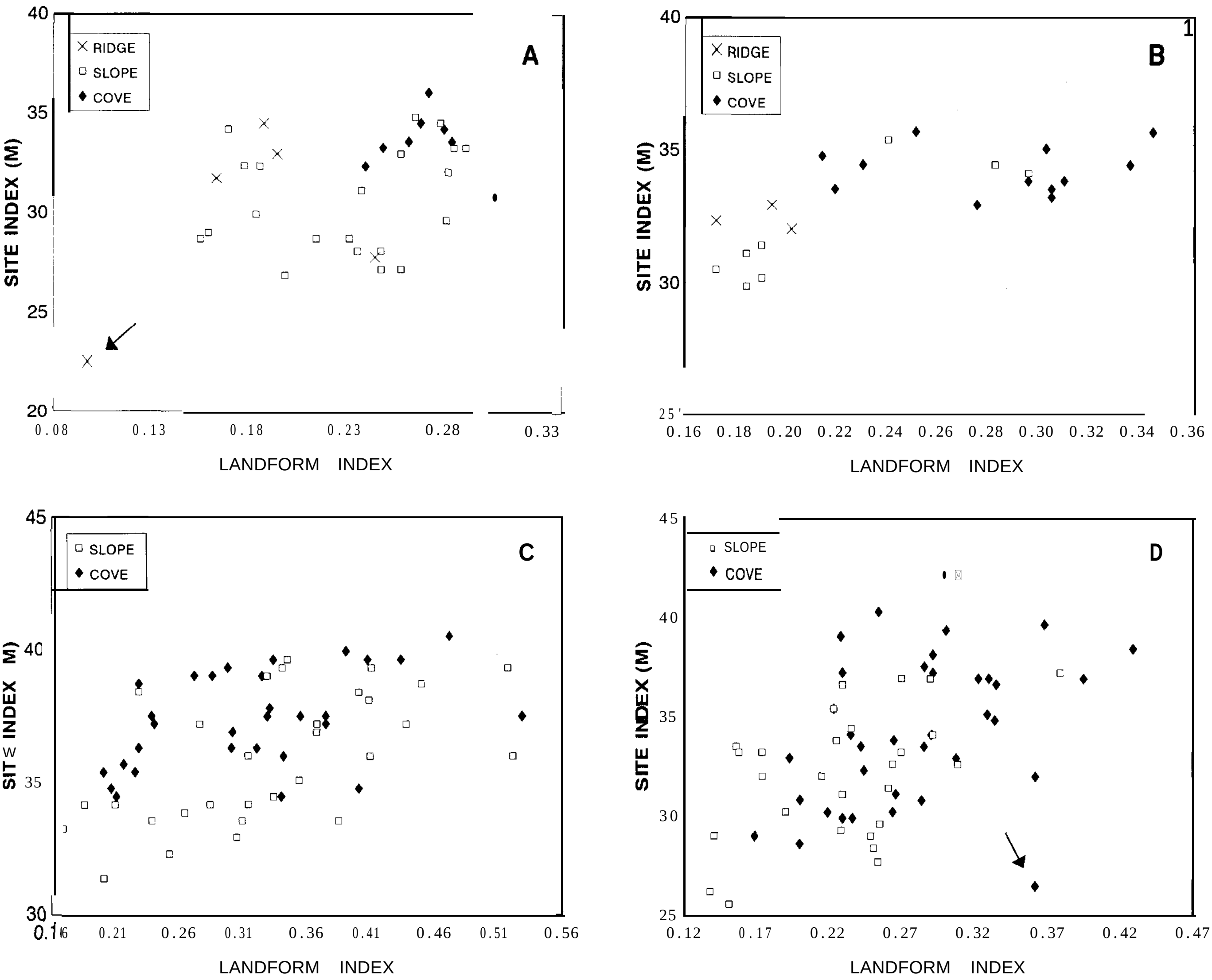

FIG. 3. Association of yellow-poplar site index with landform index at each study location: (A) Bent Creek (n = 34, $r = 0.45$), (B) Nantahala Mountains ($n = 24$, $r = 0.65$), (C) Bald Mountains ($n = 60$, $r = 0.47$). (D) southern Appalachians ($n = 64$, $r = 0.49$). The sample site designated by an arrow in 3A and 3D is discussed in the text.

affected by one or more plots with relatively low site index and landform index. Without the influence of those plots, the relationship between site index and landform index would have been much weaker and possibly not significant, especially at Bent Creek. The low correlation at Bent Creek might be partially explained by the smallness of the geographic area in which sites were sampled. The relationship between site index and landform index at Bent Creek would have been even weaker in the absence of the strong influence of a ridge site (indicated by an arrow). In contrast, plots of site index by landform index for the two extensive data sets (Figs. 3C and 3D) were more evenly distributed over the range of measured landform index and are less influenced by a few outlying plots. At all locations, plot values of site index were generally higher for cove landforms than for slope or ridge landforms, but there were many exceptions to this rule.

Some of the variation in site index can be attributed to sources other than variation in landform. For example, the southern Appalachian plot datum identified by the arrow (Fig. 3D) appear anomalous; a relatively low value of site index is associated with a cove landform and high value of landform index. However, the plot in question has a south aspect and convex surface shape, both of which contribute to more xeric conditions and lower site index. Also, the site index curves are a potential source of error. Beck and Trousdell (1973) suggested that problems such as sampling bias in curve construction and assumptions about shape of the height-growth curve can lead to serious bias in estimates of site index.

Regression analysis was used to establish the mathematical relationship of site index to landform index for each location. Examination of the plotted data (Figs. 3A–3D), especially that for the Nantahala Mountains location (Fig. 3B), suggests that the trend is slightly curvilinear. However, a linear function was used for all locations because the study was not designed with the objective of determining the best form for a predictive model. Site index was regressed on landform index for each location (Table 5) and the regressions were plotted on common axes (Fig. 4). A test for common regressions revealed that both slope and levels varied significantly among

TABLE 5. Parameter estimates and linear correlations for relationship of yellow-poplar site index as a function of landform index at four locations in the Blue Ridge province

Location	*n*	B_0 ± RMSE	B_1 ± RMSE	*r*	$\overline{SI}$
Bent Creek	34	24.7±2.3	27.4±9.6	0.45	31.1
Nantahala Mountains	24	28.2f1.3	20.7±5.1	0.65	33.2
Bald Mountains	60	32.7±1.0	12.2±3.0	0.47	36.6
Southern Appalachians	64	25.8±1.8	29.81t6.7	0.49	33.5

NOTE: The relationship between site index (SI) and landform index is defined as SI = $B_0 + B_1$ (landform index), where B_0 and B_1 are regression coefficients. RMSE, root mean square error.

TABLE 6. Correlation (*r*) of site index with topographic variables by study location

Topographic variable	Bent Creek	Nantahala Mountains	Bald Mountains	Southern Appalachians
Elevation	0.04	0.23	−0.34*	0.18
Cosine of aspect	−0.37*	-0.22	0.22	0.16
Gradient	0.29	0.13	0.00	0.09
Slope position	-0.10	-0.10	0.16	0.21
Terrain shape index	0.51*	0.41*	0.43"	0.34*
Landform index	0.45*	0.65"	0.47*	0.49*

*$p < 0.05$.

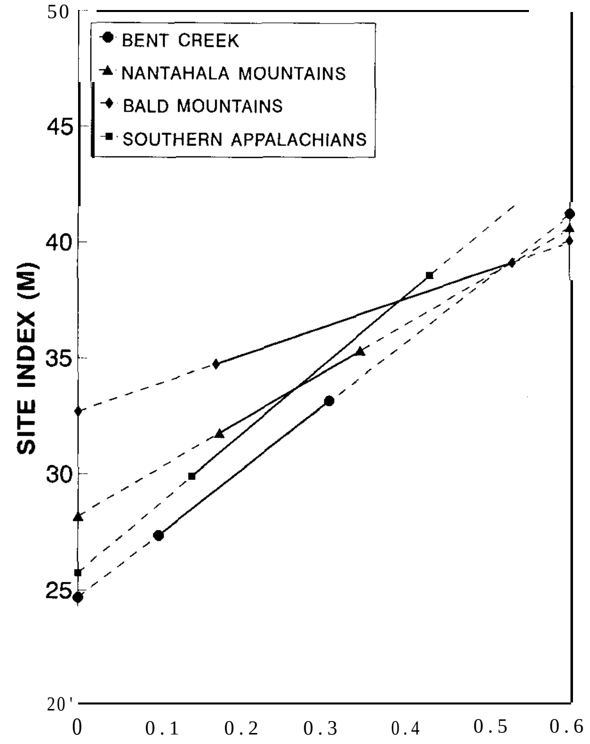

FIG. 4. Comparison of linear models for predicting site index from landform index at each location over range of field data (solid line) and extrapolated (broken lines).

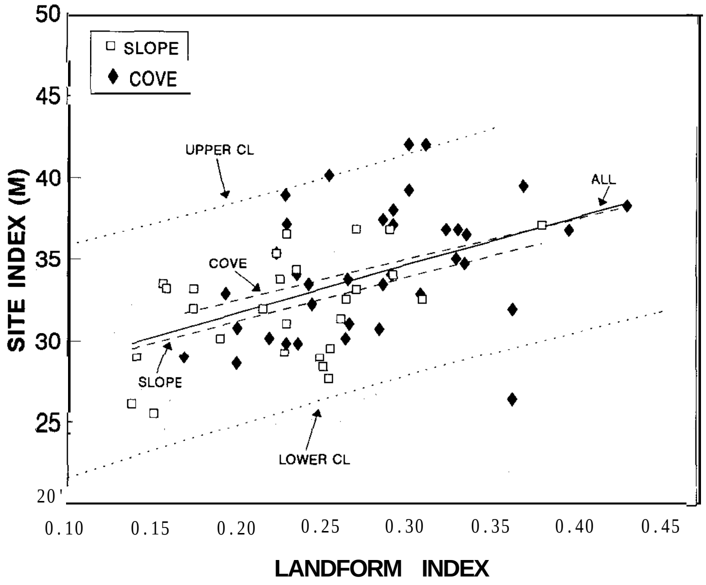

FIG. 5. Comparison of landform index with site index for the southern Appalachians with all landforms combined and by slope and cove landforms. Two curved dotted lines indicate upper and lower 95% confidence limits for prediction of future individual values.

locations and therefore data could not be pooled for further analysis. These results imply that yellow-poplar site index is directly associated with landform index over a broad geographic area, but that the response varies by location.

Figure 5 illustrates a linear model that expresses the relationship between site index and landform index on all landforms in the southern Appalachians, and the 95% confidence limits for future individual estimates. The simple model accounts for about 24% of the variation in site index and predicts that a change of 0.01 in landform index will result in a change of 0.3 m in site index. Linear models were also developed for cove and slope landform classes and are shown as broken lines. Slopes of the two classes did not differ significantly, and indicate a common response of yellow-poplar site index to changes in landform index.

Soil–site relationships

Site index of yellow-poplar was weakly correlated with most conventional soil–site variables (Table 6). Only landform index and terrain shape index were significantly correlated with site index at each of the four locations. I used data from plots in the southern Appalachians to develop a preliminary multivariate model to predict site index. Correlations between site index and topographic variables were generally poorer for plots in the southern Appalachians than for plots in the other three locations.

Initially, all topographic variables were included in a multiple regression analysis. However, partial regression coefficients of only three variables (landform index, terrain shape index, and cosine of aspect) were significant at $p = 0.10$. Inclusion of these variables in a predictive model explained about 31% of the variation in site index, with a standard error of 3.3 m. These topographic variables explained a relatively small proportion of the variation in site index and much remains to be accounted for by other site variables, such as soil and climate. Also, better results might have been obtained by using tree height as the dependent variable and including tree age as an independent variable (McNab 1989). However, Della-Bianca and Olson (1961) reported relatively poor results in predicting height of yellow-poplar as a function of tree age and other site factors and attributed the excessive unexplained variation to unmeasured soil properties over the broad geographic area where their study was conducted.

Standard partial regression coefficients were calculated to determine the relative importance of each independent variable in predicting site index. The magnitudes of the coefficients (landform index = 0.49; terrain shape index = 0.22; cosine of aspect = 0.19) indicate that landform index has approximately twice as much effect on predicted site index as either of the other variables. The importance of terrain shape index and aspect are similar.

A potential problem in using the landform index in soil–site type models is intercorrelation with other variables associated with soil moisture relations. For example, landform index was significantly correlated ($p < 0.05$) with elevation (r = 0.31–0.78) and terrain shape index (r = 0.30-0.57) at all locations, which may cause estimates of regression coefficients to be unstable when these variables are included in prediction equations. However, elevation and the two indexes account for different sources of variation in tree growth and I use ridge regression to partly overcome problems of moderate multicollinearity (Afifi and Clark 1990).

In summary, the landform index is simple in concept, easy to apply, and objective. It is superior to a number of conventional variables in accounting for variation in site productivity of a mesophytic tree species in mountainous topography. I did not determine what environmental factors caused the site index of yellow-poplar to vary from site to site. However, yellow-poplar is a mesophytic species and its increased growth on sites with higher landform indexes is likely caused by favorable environmental factors associated with large concave landforms such as increased topographic shading (Lee and Baumgartner 1966). Auten (1945) attributes the higher site index of coves to protection from "drying winds," which could affect evaporation and transpiration. McConathy (1983) found that stomatal density of yellow-poplar leaves was greater on xeric sites compared to mesic sites, suggesting greater transpiration rates and perhaps reduced growth rates on ridge and slope sites where soil moisture deficits would likely occur first. A definitive explanation for the growth response of trees to complex environmental relationships in forest stands will likely be difficult to obtain for reasons summarized by Jarvis and McNaughton (1986). As Peet (1978) suggests, ". ..no simple measure [is] available which incorporates all the important components of site moisture." Additional field study is needed to clarify ecological relationships associated with landform and the correlation of landform index with occurrence and growth of other tree and shrub species.

NOTE ADDED IN PROOF: After this manuscript was accepted for publication, I learned that Pyatt et al. (1969) described an experimental method for classifying stand exposure to the wind. The method is more fully described by Wilson (1984) as "a numerical measure of the degree of shelter afforded a defined location by the surrounding topography." The procedure that I used to determine landform index is almost identical to the method described by Pyatt et al. and Wilson.

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