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Scott R. Abella

University of Nevada, Las Vegas, scott.abella@unlv.edu

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QUANTIFYING ECOSYSTEM GEOMORPHOLOGY OF THE SOUTHERN APPALACHIAN MOUNTAINS

Scott R. Abella

**Ecological Restoration Institute
Northern Arizona University
Flagstaff, Arizona 86011-5017**

Abstract: Geomorphology is a dominant factor influencing vegetation distribution in the southern Appalachians, and quantifying landform characteristics is increasingly important for forest ecosystem classification. This study used slope gradient and two previously published geomorphic indices, terrain shape index and landform index that quantify landform shape and protection, to develop a field-based landform quantification system at four study areas in the southern Appalachians. Six major landform types (ridge-tops, nose slopes, linear hillslopes, coves, stream ravines, and stream bottoms) exhibited quantitatively different characteristics, and these differences among landforms were not evident when using only categorical landform descriptions (e.g., convex, concave) that have been most common in southern Appalachian ecological research. Discriminant function resubstitution based on quantitative geomorphic variables distinguished 78% or more of categorical landform types, and misclassifications partly resulted from inadequacies of categorical data for capturing the continuum of landform characteristics. I applied the geomorphic quantification system by developing a classification tree model to predict the presence or absence of eastern hemlock (*Tsuga canadensis*) ecosystems in northwestern South Carolina. The quantitative model correctly identified 86% of sites actually supporting a hemlock ecosystem, substantially higher than a model using categorical landform data that correctly identified only 57% of hemlock sites. [Key words: ecosystem classification, terrain shape index, landform index, eastern hemlock.]

INTRODUCTION

Southern Appalachian landscapes consist of a myriad of landforms of various sizes and shapes, each providing different environmental complexes on which to support vegetation assemblages (Day and Monk, 1974; McNab et al., 1999). Landform description has long been recognized as essential for understanding vegetation distribution in the southern Appalachians (Bowman, 1911; Whittaker, 1956; Parker, 1982). Categorical landform descriptions, such as landform type (e.g., ridge-top, cove) or shape (convex, linear, concave), have been most common in southern Appalachian research (Whittaker, 1956; Golden, 1981). Parker (1982) was among the first to quantify landform characteristics to predict vegetation distribution, by developing a topographic relative moisture index integrating the effects of slope gradient, aspect, hillslope shape, and topographic position on potential soil moisture availability. Callaway et al. (1989) quantified landform site protection using an index based on the relative elevations of landforms surrounding a site and distances from a site to those landforms. McNab (1989, 1993) published two geomorphic indices, terrain shape index and landform index, which quantify landform shape

and protection. Both indices predicted tulip-poplar (*Liriodendron tulipifera* L.) site index in western North Carolina forests better than categorical descriptors of landforms (McNab, 1993).

In addition to being associated with forest productivity, geomorphology is a key component of ecosystem classification systems because landforms are relatively stable landscape features (Barnes et al., 1982; Host and Pregitzer, 1992). Ecosystem classification and forest management on an ecosystem basis are increasing in the southern Appalachians (McNab et al., 1999; Carter et al., 2000). Future advances in ecosystem classification science in the southern Appalachians will likely be linked with increased understanding and quantification of geomorphology and its influences on soil properties, disturbance regimes, and vegetation distribution (Abella et al., 2003). Furthermore, quantitative geomorphic data are more tractable than categorical data in the multivariate analyses increasingly used during ecosystem classification to discern ecological interrelationships (Hix and Pearcy, 1997).

This study was undertaken to extend advances in landform quantification to facilitate advances in ecosystem classification science in the southern Appalachians. Specific study objectives were to evaluate modifications to McNab's (1989) terrain shape index to improve measurement replicability, and to develop a quantification system using existing geomorphic indices that distinguishes between southern Appalachian landforms. An application of the landform quantification system is illustrated by predicting the distribution of eastern hemlock (*Tsuga canadensis* (L.) Carr.) ecosystems in northwestern South Carolina.

METHOD

Study Areas

This study included four study areas, Jocassee Gorges and the Ellicott Rock Wilderness in northwestern South Carolina, and the Shining Rock Wilderness and Great Smoky Mountains National Park in western North Carolina, to encompass a range of southern Appalachian geomorphology (Fig. 1). The primary study area was the South Carolina Department of Natural Resources' 13,000-ha Jocassee Gorges, for which I previously developed an ecosystem classification (Abella et al., 2003). Jocassee Gorges occupies the first chains of mountains that rise abruptly from the lower elevation Piedmont region, and typical elevations range from 350–850 m. Although elevations are higher in the Ellicott Rock Wilderness (typical elevations 500–1200 m), hillslopes are more undulating and less dissected than those of Jocassee Gorges (Abella and Shelburne, 2003). Elevations in the Shining Rock Wilderness range from 960–1930 m, and elevations are about 1250–1600 m in the areas studied in eastern Great Smoky Mountains National Park (Rough Fork and Flat Creek trail areas; 35°35'N, 83°09'W). All study areas are part of the oak-chestnut forest region covering much of the southern Appalachians (Braun, 1950). Jocassee Gorges is termed the Jocassee data throughout this paper, and the combined data from the other study areas are termed the validation data used to determine if this study's findings are regionally applicable.

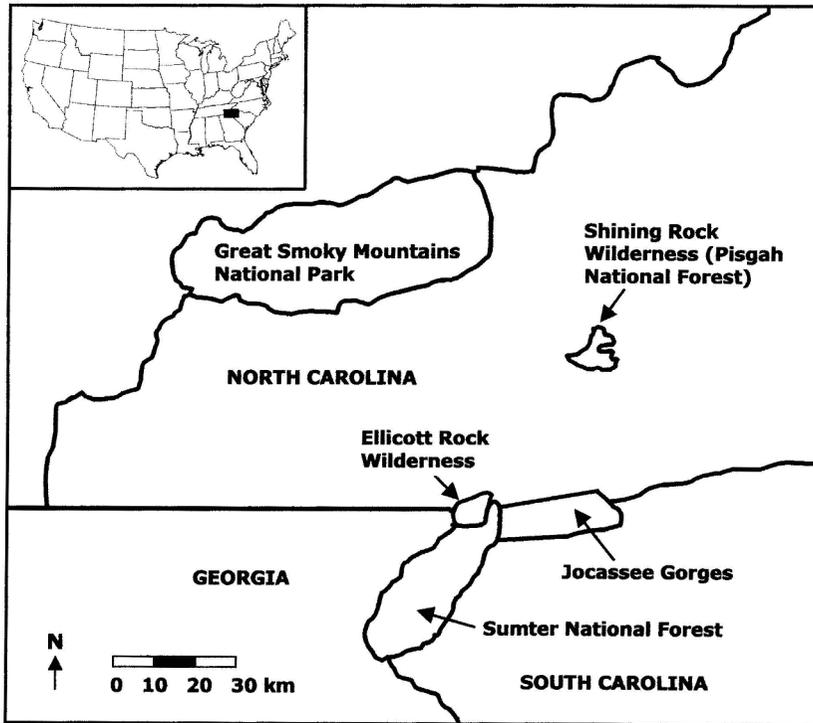


Fig. 1. Location of the Jocassee Gorges, Ellicott Rock Wilderness, Shining Rock Wilderness, and Great Smoky Mountains National Park study areas.

Landform Sampling

This study was designed to simulate procedures that might occur for field ecosystem classification or mapping. In Jocassee Gorges, 11 transects parallel to the contour were randomly located in late-successional forests older than 70 yrs. (based on stand records), and 10 landforms were sampled per transect. Transect length varied and landforms were sampled at each change of landform type, resulting in numbers of landform samples approximately proportional to each landform's occurrence. On each landform, I categorized landform type as one of the common descriptors of southern Appalachian landforms: ridgetops, nose slopes, linear hillslopes, coves, stream ravines, or stream bottoms (Hack and Goodlett, 1960; Smalley, 1984; Sherrill, 1997). I measured landform index following McNab (1993), based on the average of eight clinometer measurements to the nearest percent at 45° intervals to the tops of landforms surrounding a site (Fig. 2). Landform index is measured to the horizon and quantifies broad-scale topographic protection; there is no fixed minimum or maximum although values usually range from -2 (low protection such as on ridgetops) to 50 (high protection such as in stream ravines). Sampling occurred in April 2002 and represents leaf-off measurements. Differences between leaf-on and

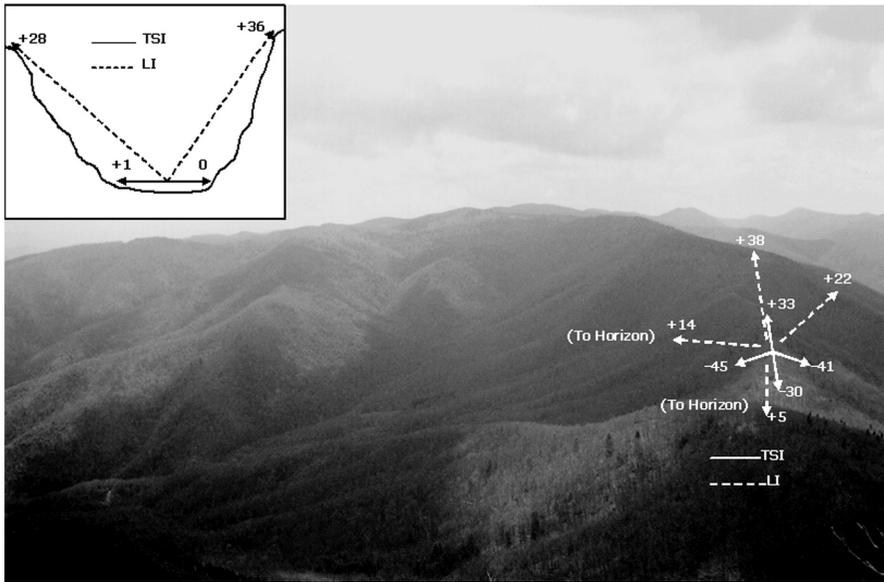


Fig. 2. Example measurements for terrain shape index (TSI) and landform index (LI) for a stream bottom (inset) and a nose slope 1 km south of Cold Mountain, Shining Rock Wilderness, North Carolina (photograph). For simplicity, only measurements across the landform are shown in the inset and measurements upslope, downslope, and across the landform are shown in the photograph. The photograph is a typical view of the mountainous topography of the southern Appalachians, illustrating the high geomorphic variability of the landscape. Photo by S. R. Abella, April 15, 2002.

leaf-off measurements to the horizon for landform index are negligible, typically less than 2%.

Terrain shape index (McNab, 1989) quantifies local topographic shape (Fig. 2), and usually ranges from -24 (convex) to greater than 15 (concave). Rather than measuring terrain shape index at a fixed distance (e.g., 20 m) as originally proposed to standardize the index (McNab, 1989), I allowed measurement distances to fluctuate with the landform to try to reduce measurement error. I made measurement sightings to where the local measurement landform ended and a different landform began. This modification also should expedite terrain shape index measurements for field ecosystem mapping since horizontal distances do not need to be measured. However, this modification requires the user to recognize a change in landform shape, where measurement distance for an individual terrain shape measurement should stop. This stopping point can be recognized as the location at which a linear clinometer sighting would no longer follow the shape of the local topography. I began terrain shape index measurements in the downhill direction of the landform, and computed the index as the average of eight clinometer measurements to the nearest percent at 45° intervals following McNab (1989). I measured slope gradient to the nearest percent with a clinometer and recorded slope aspect to the nearest degree using a compass. Aspect was transformed following Beers et

al. (1966). On each landform, I also classified the ecosystem type based on methods in Abella et al. (2003), providing hemlock ecosystem presence/absence data for predictive modeling.

I collected the same data as at Jocassee Gorges, with the exception that ecosystem data were not collected, on 30 landforms in the Ellicott Rock Wilderness, 20 landforms in the Shining Rock Wilderness, and 20 landforms in Great Smoky Mountains National Park. To determine the reproducibility of measurements, I made a repeated measure in all study areas on every five landforms for terrain shape index and every 10 landforms for landform index.

Data Analysis

I computed repeated measurement error as the relative percent difference between original and repeated measurements ($(|original\ measure - repeated\ measure|/original\ measure) \times 100$). Landforms served as sampling units for statistical analyses (Hurlbert, 1984). Mean landform index, terrain shape index, and slope gradient were compared among landforms separately for the Jocassee and the validation data using one-way analysis of variance and Fisher's least significant difference (SAS Institute, 1999). Raw data approximated normality (Shapiro-Wilk test) and equal variance assumptions (Levene test). To assess multivariate differences in combinations of geomorphic variables among landforms, I used principal components analysis (correlation matrix) and multiresponse permutation procedures (Euclidean distance, default group weighting, nonrank transformed distance matrix) in the software PC-ORD (McCune and Mefford, 1999). When significant differences occurred for an overall permutation procedure test, I separated groups using pairwise comparisons (McCune and Mefford, 1999). I used discriminant analysis (SAS Institute, 1999) with proportional priors to determine the ability of the three geomorphic variables to distinguish landform types. Discriminant functions were validated by cross-validation (jackknifing) within data sets and by reciprocating discriminant functions between the Jocassee and the validation data. This reciprocating procedure provides an independent and stringent test of the capability of the geomorphic variables to distinguish landforms regionally. To assess the utility of the geomorphic variables for predicting the distribution of hemlock ecosystems in Jocassee Gorges, I used classification trees (default settings) in S-PLUS software (Insightful Corporation, 2001).

RESULTS AND DISCUSSION

Measurement Considerations

Although landform and terrain shape index have been used in several studies (McNab, 1993; Hutto et al., 1999; Carter et al., 2000), with the exception of Abella et al. (2003) no attention has been given to the reproducibility of measurements for these indices. Abella et al. (2003) reported a low repeated measurement error of 4.3% for landform index, but a high measurement error of 58.4% that precluded the use of terrain shape index in statistical analyses for the study. In the present

study, repeated measurement errors remained low for landform index for both the Jocassee ($2.1 \pm 0.5\%$ [mean \pm SE], $n = 11$) and the validation data ($2.9 \pm 1.0\%$, $n = 7$). By allowing measurement distance to fluctuate with the landform, measurement errors for terrain shape index ($6.4 \pm 1.7\%$, $n = 22$ Jocassee data, $5.4 \pm 2.6\%$, $n = 14$ validation data) decreased more than 50% from my previous report (Abella et al., 2003). Terrain shape index measurement errors, however, remained greater than those for landform index. Measurement errors for terrain shape index were highest for linear topography such as hillslopes that have index values near zero. Because of these near zero index values, even small differences between original and repeated values mathematically result in high repeated measurement errors. A way to address this is to compute repeated measurement error differently for terrain shape index by summing the absolute values of the eight measurements made to compute the index, and then comparing the sums of the original and repeated measurements. This alternative calculation should provide measurement error estimates more consistent with field measurement procedures as long as the sign (positive or negative) of measurements is consistent between original and repeated measures.

The location and scale at which terrain shape index is measured affects index values. For example, if terrain shape measurements are taken from the streambed of a small V-shaped ravine of a first-order stream, the index value will be high to indicate concave geomorphology. However, if measurements are taken from the sides of the ravine, terrain shape index will be near zero and portray the linear topography of the ravine walls. Landform index, however, will be high both on the streambed and on the ravine walls because of the broader-scale topographic protection of the entire ravine landform (McNab, 1993). Terrain shape index thus is extremely location-specific, and preliminary sampling might be helpful to select an appropriate landform scale for measurements if terrain shape index is used in a study.

Index values based on four measurements and based on eight measurements were highly correlated (Pearson $r = .98$) for both landform and terrain shape index. Measuring a landform at 90° intervals, upslope and downslope parallel to the landform and across the landform, provides index values nearly identical to values based on eight measurements at 45° intervals. These results support the conclusions of McNab (1989, 1993), although eight measurements have traditionally been taken in applications (McNab, 1993). While time saved by taking only four measurements is minimal since measuring these indices is already rapid for eight measurements (about 1 min. required per index), results suggest there is little advantage to using eight rather than four measurements in future applications of landform and terrain shape index.

Quantifying Landform Characteristics

Mean landform index, indicative of topographic protection, was significantly lower on ridgetops than on the other five landform types for both the Jocassee and the validation data (Table 1). Ridgetops for the higher-elevation validation landscapes exhibited lower landform indices than ridgetops for the Jocassee data, reflecting the minimal topographic protection on high-elevation ridgetops. In Jocassee Gorges, stream ravines and bottoms exhibited the highest landform

Table 1. Summary of One-Way Analyses of Variance of Geomorphic Variables among Landforms of the Southern Appalachian Mountains, South and North Carolina, for Two Data Sets Totalling Four Landscapes^a

Variable	Measure	Landform type						F	P	LSD ^b
		Ridgetop	Nose slope	Hillslope	Cove/ headslope	Stream ravine	Stream bottom			
Jocasse data		n = 7	n = 14	n = 41	n = 20	n = 21	n = 7			
Landform index	Mean ^c	10 d (57)	17 c (36)	28 b (34)	31 ab (21)	37 a (22)	35 a (29)	19.0	<.0001	6.5
	Range ^d	1,17	8,27	9,53	19,41	24,51	20,50			
Terrain shape index	Mean	-15 d (50)	-14 d (46)	1 c (1046)	24 b (30)	30 a (24)	1 c (278)	126.8	<.0001	5.2
	Range	-23,-3	-24,-1	-13,24	9,38	17,41	-3,8			
Slope gradient (%)	Mean	21 bc (48)	28 b (55)	61 a (28)	26 b (53)	14 cd (72)	7 d (58)	43.7	<.0001	11.5
	Range	6,34	6,56	16,94	12,60	2,37	1,15			
Validation data		n = 8	n = 9	n = 23	n = 10	n = 15	n = 5			
Landform index	Mean	4 d (80)	15 c (48)	23 b (37)	24 b (21)	32 a (23)	20 bc (30)	18.6	<.0001	6.6
	Range	0,8	3,27	12,41	14,30	16,46	13,29			
Terrain shape index	Mean	-5 d (68)	-9 d (54)	1 c (325)	17 b (33)	25 a (26)	2 c (131)	84.6	<.0001	4.6
	Range	-9,-2	-17,-1	-6,8	11,29	14,42	-1,5			
Slope gradient (%)	Mean	8 d (77)	21 bc (53)	44 a (44)	27 b (37)	14 cd (62)	6 d (60)	16.3	<.0001	12.5
	Range	2,19	7,42	21,88	13,39	4,28	2,9			

^aMeans within a row without shared letters differ at $P < .05$.

^bLeast significant difference.

^cValues are mean (coefficient of variation).

^dValues are minimum, maximum.

indices, with coves and hillslopes intermediate but sharply higher than landform indices of nose slopes and ridgetops. Trends were similar for the validation data, with the exception that landform indices for stream bottoms were about 15 units lower than for the Jocassee data. Reasons for this difference are unclear but might be related to a greater number of large-sized stream bottoms that have lower topographic protection on the validation landscapes.

Multiple comparison results for terrain shape index, quantifying local topographic shape, were identical for the Jocassee and the validation data (Table 1). Terrain shape index was most negative on ridgetops and nose slopes (convex landforms), near zero on hillslopes and stream bottoms (linear landforms), and highest in coves and stream ravines (concave landforms). Mean slope gradient was highest on hillslopes for both data sets, and lowest on stream bottoms, stream ravines, and ridgetops. Slope gradients on hillslopes averaged 17% higher in Jocassee Gorges compared to the validation landscapes, reflecting the steep gorge topography characteristic of Jocassee Gorges (Cooper and Hardin, 1970).

In overall tests using multivariate multi-response permutation procedures, combinations of landform index, terrain shape index, and slope gradient differed among landform types for both the Jocassee ($T = -35.9$, $A = 0.46$, $P < .0001$) and the validation data ($T = -23.4$, $A = 0.43$, $P < .0001$). Pairwise comparisons within each data set were significant ($P < .05$) between each pair of landform types except for between ridgetops and nose slopes ($P = .24$) of the Jocassee data. Ridgetops and nose slopes did not differ in Jocassee Gorges because elevations of ridgetops were not high enough to produce the low landform indices typical of higher elevations, and because few large, relatively flat ridgetops with terrain shape indices near zero exist in Jocassee Gorges (Table 1). Ecosystem composition is similar on ridgetops and nose slopes in Jocassee Gorges (Abella et al., 2003), so in practice distinguishing these landforms for ecosystem classification might not be important on this landscape.

This landform quantification system using landform index, terrain shape index, and slope gradient might help clarify confusion about categorical landform type descriptions. For example, coves have been variously described as some sort of oval valley (Fenneman, 1938; Braun, 1950). Often it is unclear, however, whether this description also includes smaller V-shaped stream ravines or other areas of concave geomorphology. In this study, V-shaped ravines were termed stream ravines, relatively flat terrain near streams was termed stream bottoms, and three-sided concave landforms often at the headwaters of first-order streams were termed coves/head-slopes. These three landforms, concave in broad-scale geometry, exhibited different quantitative characteristics (Table 1), suggesting that when detailed geomorphic descriptions are needed terming all concave landforms as "coves" masks the variability of concave topography. Distinctions among concave landforms are important for ecosystem classification because in Jocassee Gorges, for example, stream bottoms exclusively supported hemlock ecosystems whereas coves supported either tulip-poplar or oak (*Quercus*) ecosystems (Abella et al., 2003).

Table 2. Discriminant Functions Based on Geomorphic Variables for Landforms of the Southern Appalachian Mountains, South and North Carolina, for Two Data Sets Totaling Four Landscapes

	Landform type						Overall
	Ridgetop	Nose slope	Hillslope	Cove/ head-slope	Stream ravine	Stream bottom	
Jocassee data	<i>n</i> = 7	<i>n</i> = 14	<i>n</i> = 41	<i>n</i> = 20	<i>n</i> = 21	<i>n</i> = 7	<i>n</i> = 110
Constant	-8.67	-10.40	-11.65	-10.97	-16.36	-17.27	
Landform index	0.31	0.45	0.30	0.32	0.51	0.90	
TSI ^a	-0.54	-0.59	-0.24	0.36	0.41	-0.43	
Slope gradient	0.04	0.04	0.22	0.00	-0.12	-0.21	
RS % correct ^b	29	71	93	85	71	100	81
CV % correct ^c	0	64	93	85	71	86	77
Validation data	<i>n</i> = 8	<i>n</i> = 9	<i>n</i> = 23	<i>n</i> = 10	<i>n</i> = 15	<i>n</i> = 5	<i>n</i> = 70
Constant	-3.54	-10.99	-8.44	-9.68	-19.26	-11.08	
Landform index	0.26	0.77	0.46	0.32	0.76	0.99	
TSI ^a	-0.39	-0.92	-0.37	0.47	0.58	-0.52	
Slope gradient	-0.02	-0.10	0.10	-0.01	-0.26	-0.30	
RS % correct ^b	100	89	100	90	93	100	96
CV % correct ^c	88	78	100	80	93	100	91

^aTerrain shape index.

^bPercent classified correctly by resubstitution using the discriminant function.

^cPercent classified correctly by cross-validation (jackknifing).

Distinguishing Categorical Landforms

Based on landform index, terrain shape index, and slope gradient, discriminant functions by resubstitution distinguished 81% of categorical landform types for the Jocassee data and 96% for the validation data (Table 2). Jackknifing reduced overall classification success by only 5% or less, indicating within-data set robustness of the discriminant functions. Reciprocating discriminant functions provided a 78% (86/110) classification success for the Jocassee data and an 83% (58/70) classification success for the validation data. This robustness of the discriminant functions for quantifying landforms among landscapes suggests that this study's findings are regionally applicable.

Misclassifications for the Jocassee discriminant functions were primarily related to difficulties distinguishing ridgetops from nose slopes and stream ravines from coves. In jackknife analyses, all seven ridgetops were misclassified as nose slopes, and all six misclassified stream ravines were classified as coves. Ridgetops and nose slopes were distinguished with higher accuracy on the validation landscapes, probably because landform indices on ridgetops were sharply lower than on nose slopes in the higher-elevation validation landscapes. Discriminant functions distinguished

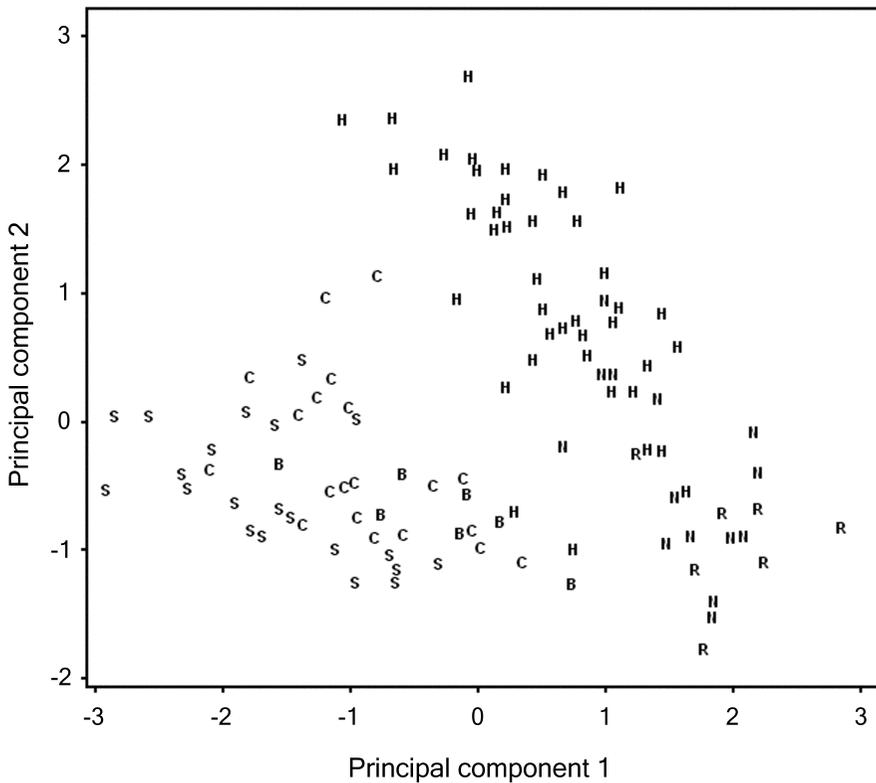


Fig. 3. Principal components analysis ordination of the continuum of landforms based on slope gradient, terrain shape index, and landform index for Jocassee Gorges, northwestern South Carolina. Principal component 1 explained 56% of the variance and had high eigenvectors for terrain shape index (-0.72) and landform index (-0.67). Principal component 2 explained 36% of the variance and had a high eigenvector for slope gradient (0.92). R = ridgetop, N = nose slope, H = hillslope, C = cove, S = stream ravine, and B = stream bottom.

landforms about 15% more accurately in the validation landscapes than in Jocassee Gorges, which is known for variable, highly dissected topography typical of the edge of the Blue Ridge escarpment (Cooper and Hardin, 1970).

I also examined raw data and my field notes to assess why misclassifications occurred, and for more than half the misclassifications I had noted in the field difficulty in placing the landform into one of the six categorical landform types. Since landforms occur on a continuum that cannot always be readily categorized (Fig. 3), many misclassifications seem more related to inadequacies of forcing landforms into categories than they are to shortcomings of the quantitative geomorphic variables. Categorical descriptions are valuable for describing basic landform characteristics and remain important in southern Appalachian ecological research. However, since the landform quantification system readily distinguished perceived landform categories (Table 2), quantifying landform characteristics is an alternative

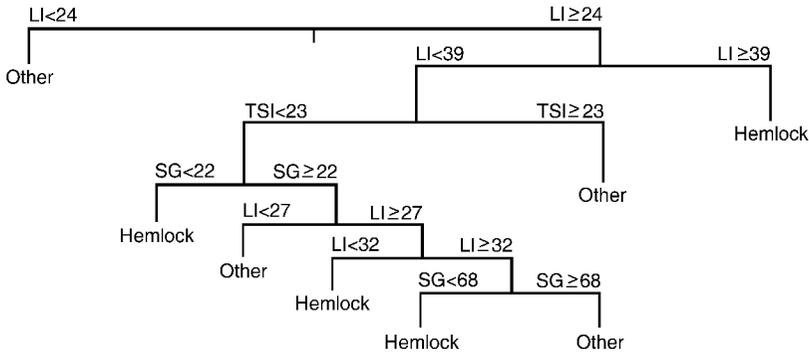


Fig. 4. Classification tree model predicting the presence or absence of hemlock ecosystems based on geomorphic variables for Jocassee Gorges, South Carolina. Terrain shape index is negative on convex geomorphology, near zero on linear geomorphology, and positive on concave geomorphology. Higher landform indices indicate greater topographic protection, such as in stream bottoms. LI = landform index, TSI = terrain shape index, SG = slope gradient.

to categorizing landforms that more accurately portrays the continuum of landform characteristics, provides data more tractable in statistical analyses especially since there is no clear way to order landform type data, and avoids confusion about the geometries of categorical landform descriptions.

Predicting Ecosystem Distribution

Based on the geomorphic variables of landform index, terrain shape index, and slope gradient, I developed a classification tree model (Breiman et al., 1984) to predict the presence or absence of hemlock ecosystems across the Jocassee Gorges landscape (Fig. 4). This model correctly classified the presence of a hemlock ecosystem on 86% (30/35) of sampled sites that actually supported a hemlock ecosystem and had an overall classification success of 90% (99/110). The quantitative geomorphic model also classified sites considerably better than a model using categorical landform type data that correctly identified only 57% (20/35) of sites actually supporting a hemlock ecosystem and produced an overall classification success of 79% (87/110). I validated the quantitative model using an independent data set from 48 plots sampled in Jocassee Gorges as part of an ecosystem classification study (Abella et al., 2003). The model also performed well on this independent data by correctly identifying 87% (13/15) of plots actually supporting a hemlock ecosystem and exhibiting an overall classification success of 83% (40/48).

In the classification model, sites are first divided into low and high landform indices and are progressively partitioned similar to a dichotomous botanical key (Fig. 4). Hemlock ecosystems occur on a range of geomorphic combinations; for example, from stream bottoms exhibiting low terrain shape indices and slope gradients, to protected hillslopes of high slope gradient with landform indices greater than 39. Transformed slope aspect was not included in the model because overall

classification success did not improve with the inclusion of aspect (90% without aspect, 90% with aspect). Hemlock ecosystems occurred on all aspects, and the distribution of hemlock was more associated with the landform variables quantifying topographic protection that may strongly influence moisture availability (Helvey et al., 1972). Because of current concerns about the impacts of the introduced hemlock woolly adelgid (*Adelges tsugae* Annand) on hemlock forests in the eastern United States (Orwig and Foster, 1998), models such as this one that relate the current distribution of hemlock ecosystems to geomorphology could provide valuable reference information should hemlock be reduced or eliminated from future southern Appalachian forests.

CONCLUSION

Geomorphology is a dominant structuring variable affecting ecosystem distribution on southern Appalachian landscapes. This study used slope gradient and two geomorphic indices, terrain shape index and landform index that quantify topographic shape and protection, to distinguish landforms and predict ecosystem distribution on a southern Appalachian landscape. A field-based classification tree model using these geomorphic variables predicted the presence or absence of eastern hemlock ecosystems with 90% accuracy. Future research in the southern Appalachians could focus on how causal factors affecting ecosystem distribution, such as rooting depth and soil moisture regimes, vary among landforms and topographic positions (Swanson et al., 1988; Yeakley et al., 1998; Dyer, 2002). If these causal factors could be correlated to key soil variables and readily measured geomorphic indices, powerful models could be made for understanding vegetation-environment relationships and patterns of ecosystem distribution across landscapes. Future advances in ecosystem classification science in the southern Appalachians will likely be linked to a better understanding of geomorphology's influence on disturbance regimes, soil properties, hydrological patterns, and how geomorphology structures the spatial scales at which ecosystems occur.

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