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Predicting Southern Appalachian overstory vegetation with digital terrain data

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Abstract

Vegetation in mountainous regions responds to small-scale variation in terrain, largely due to effects on both temperature and soil moisture. However there are few studies of quantitative, terrain-based methods for predicting vegetation composition. This study investigated relationships between forest composition, elevation, and a derived index of terrain shape, and evaluates methods for predicting forest composition. Trees were measured on 406 permanent plots within the boundaries of the Coweeta Hydrologic Lab, located in the Southern Appalachian Mountains of western North Carolina, USA. All plots were in control watersheds, without human or major natural disturbance since 1923. Plots were 0.08 ha and arrayed on transects, with approximately 380 meters between parallel transects. Breast-height diameters were measured on all trees. Elevation and terrain shape (cove, ridge, sideslope) were estimated for each plot. Density (trees/ha) and basal area were summarized by species and by forest type (cove, xeric oak-pine, northern hardwoods, and mixed deciduous). Plot data were combined with a digital elevation data (DEM), and a derived index of terrain shape at two sampling resolutions: 30 m (US Geological Survey), and 80 m (Defense Mapping Agency) sources. Vegetation maps were produced using each of four different methods: 1) linear regression with and without log transformations against elevation and terrain variables combined with cartographic overlay, 2) kriging, 3) co-kriging, and 4) a mosaic diagram. Predicted vegetation was compared to known vegetation at each of 77 independent, withheld data points, and an error matrix was determined for each mapping method.

We observed strong relationships between some species and elevation and/or terrain shape. Cove and xeric oak/pine species basal areas were positively and negatively related to concave landscape locations, respectively, while species typically found in the mixed deciduous and northern hardwood types were not. Most northern hardwood species occurred more frequently and at higher basal areas as elevation increased, while most other species did not respond to elevation. The regression and mosaic diagram mapping approaches had significantly higher mapping accuracies than kriging and co-kriging. There were significant effects of DEM resolution on map accuracy, with maps based on 30 m DEM data significantly more accurate than those based on 80 m data. Taken together, these results indicate that both the mapping method and terrain data resolution significantly affect the resultant vegetation maps, even when using relatively high resolution data. Landscape or regional models based on 100 m or lower resolution terrain data may significantly under-represent terrain-related variation in vegetation composition.

Introduction

Forest scientists and managers have long used the relationships between terrain, climate, moisture, and vegetation to map forest communities and overstory composition, both in eastern North America in general (Nichols 1935; Braun 1950; Küchler 1964), and the Southern Appalachian mountains in particular (Harshberger 1903; Cain 1931; Oosting and Bordeau 1955; Bieri and Arliot 1965; Golden 1981). Among-taxa

differences in cold tolerance, moisture response, and growth potential interact with climate, soils, and topography and result in characteristic changes in species composition on continental, regional, and local (macro-, meso-, and micro-) scales. Environmental conditions change at macro- and mesoscales due to latitudinal and continental/oceanic influences on temperature and precipitation, and to regional variation in geologic substrate and landform (Bailey 1996). Physiographic and "bioclimatic" regions have been identified and these regions have been associated with broad changes in species composition (Holdridge 1947; Bailey 1980; Bailey 1996). While many eastern north american bioclimatic regions are not adjacent nor similar in climate and taxa, e.g., boreal vs. mixed deciduous forests, there is considerable climatic and vegetation overlap among some bioclimatic regions. Environmental conditions, particularly temperature and soil moisture, may be further modified by microscale variation in landform and terrain e.g., across ridges or from coves to sideslopes. Combined micro- and mesoscale variation often result in a wide range of climatic environments in relatively small areas and sustain a wide and overlapping range of bioclimatic vegetation types in one region.

Meso- and microscale landform variation underlie a concomitant diversity in overstory vegetation types in the Appalachian Mountains of the southeastern United States (Lindsey and Sawyer 1970). Species composition and climatic variables overlap, including temperature, precipitation, and evapotranspiration, for northern hardwoods, mixed mesophytic, mixed oak, and other deciduous types common to the southern Appalachian region (Lindsey and Escobar 1976). Overlap is due in part to the large geographic extent of the physiographic provinces in which the communities are defined, and in part to the considerable terrain shape (landform) and elevational variation within the region (Whittaker 1956; Lindsey and Sawyer 1970; Lindsey and Escobar 1976; Barnes 1991).

While the idealized relationships between overstory communities and terrain for the southern Appalachians have been described (Whittaker 1956; Day and Monk 1974; Day et al. 1988), we know substantially less about how best to combine these relationships with widely available digital elevation data and their derivatives to aid in predicting the general or specific vegetation composition across the landscape (e.g., Davis and Goetz 1990). Species composition at a point on the landscape depends on interactions among site environmental conditions, prior species composition, age, sprouting ability, disturbance history, and seed availability. Specific information about terrain or elevation may aid in predicting the occurrence of species or plant communities at a given site only if there are strong relationships between environmental conditions and species requirements, and if the disturbance regime and stand histories are similar. Widely available digital terrain data allows us to identify elevation, slope, aspect, landform (terrain shape), and other derived variables at 30m and 80 m horizontal resolutions for most of the mountainous regions of North America. These terrain data may be used to map realized or potential vegetation across the landscape, however we currently don't know if these spatial resolutions are appropriate, nor how the terrain data might best be applied.

There are a number of techniques for predicting continuous and categorical data from a spatially mapped sample. "Mosaic" or "block" diagrams have been used to summarize the relationships between site elevation, landform and the expected vegetation (Whittaker 1956; Dix and Smeins 1967; Vankat 1982; Peet 1989). Axes for mosaic diagrams often use variables listed on nominal or ordinal scales, for example a moisture index from wet to dry, or aspect from north to south, which complicates application to any specific landscape. Regression models have been used successfully in a wide range of disciplines (Cressie 1991), particularly for estimating climatic variables such as temperature and precipitation at unsampled locations. Mean annual temperature typically decreases with elevation, and precipitation increases with elevation in many locations, both relationships which influence plant species distribution. Kriging and other geostatistical techniques are a third set of tools, explicitly developed for spatial predictions, however their utility in vegetation mapping is relatively untested. We may use digital terrain data with all of these methods to map potential and realized vegetation, however studies are few, and in no case do we have information on how the resolution of digital terrain data may affect our prediction accuracy.

The objectives of this work were to 1) to characterize the relationships between southern Appalachian tree species (measured by basal area and stem density) and digital elevation data and a derived index of terrain shape, 2) evaluate mosaic diagrams, linear regression models, and geostatistical methods for mapping the vegetation composition in these forests, and 3) identify the differences in map accuracy when applying DEMs with 30 m and 80 m sampling frequencies.

Materials and methods

The study was conducted within the boundaries of the U.S. Forest Service Coweeta Hydrologic Lab, a 2185 ha research forest in western North Carolina, USA. Elevation at Coweeta ranges from 700 to 1590 m, with a concomitant range in annual precipitation of 1800 to 2500 mm (Swank and Crossley 1988). Mean monthly temperature averages 21.6°C in July and 3.3°C in January, and the climate is Humid Temperate under the Köppen System (Swift et al. 1988). The bedrock is of late Precambrian origin, and soils are dominated by well-developed Ultisols and immature Inceptisols (Hatcher 1988). The forest was influenced by Native American landuse practices until 1837, including semi-annual burning. Settlers arrived in the basin in 1842 and continued the practice of burning and grazing, but also cultivated areas, primarily in valley bottoms. Logging was conducted primarily from 1919 to 1923, removing most trees over 40 cm diameter at breast height (DBH, 1.3 m). The U.S. Forest Service then took over administration of the area, and there were no major human disturbances of these control watersheds after 1923.

Trees were measured on 406 permanent plots in the Coweeta Basin. Thirteen inventory transects at 200 m intervals were established on a bearing of 330° across the Coweeta basin. Each transect was divided into 0.08 ha plots with dimensions of 20 m by 40 m. Plot sample data analyzed here are part of a larger time series dating back to the 1930s, and traditional community analyses and temporal dynamics are reported in a separate paper (Elliot et al. 1997). Data used in the present analyses are based on remeasurements conducted from 1972 to 1992. All plots selected in our analyses were in control watersheds, which have been without human disturbance since 1923 (Douglass and Hoover 1988). Breast-height diameter was measured on all trees greater than 1.5 cm using a diameter tape, placed into 2.5 cm diameter classes, and recorded by species. Basal area per tree was calculated from tree diameter, heights were measured using a clinometer, and plot terrain position (cove, ridge, sideslope) was ocularly estimated. Plot center locations on digital maps were verified for a subset of plots by comparing plot location to known features such as road and stream crossings, identifiable ridge and cove locations, and by global positioning system coordinate measurements; tested plot centers were always within plot boundaries.

Vegetation data were summarized by plot, and community types identified using published types and previous work on species groupings (Braun 1950; Whittaker 1956; Day and Monk 1974; Eyre 1980; Day et al. 1988), and cluster analysis of this data set, reported elsewhere (Elliot et al. 1997). Densities and basal area were determined for tree species on each plot, and plot totals calculated. Basal area per plot was summed by species for each of four vegetation types: cove (*Liriodendron tulipifera, Betula lenta, Magnolia spp.*), xeric oak-pine (*Quercus coccinea, Q. prinus, Oxydendrum arboreum, Pinus rigida*), northern hardwoods (*Acer saccharum, Tilia spp., Betula alleghaniensis, Aesculas octandra*), and mixed deciduous (typically *Q. alba, Q. rubra, Robinia psuedoaccacia* and *Carya* spp.). Basal area was summed by type within the plot, and plot vegetation type was assigned to the type with the highest summed basal area. Summary statistics were computed for each vegetation type.

To determine the affect of spatial resolution on type mapping, digital elevation data were obtained and digital terrain shape derived from two common digital data sources which differed in spatial sampling frequency. The first set of digital data was based on U.S. Geological Survey (USGS) DEMs produced using an optical-mechanical photomapper (USGS 1990). These data were delivered with a 30 meter horizontal posting frequency and a reported 7 meter vertical accuracy. The second set of data was derived from U.S. Defense Mapping Agency digital terrain models, with an 80 m horizontal posting frequency (USGS 1990) with unreported accuracy. All elevation data were projected to Universal Transverse Mercator coordinates. Slope and aspect were determined for each plot and for the entire study area using a third-order finite difference method (Skidmore 1989). Digital terrain shape was determined using a modified version of McNab's (1989) terrain shape index, a scaled 9-cell weighted average. This average sums values over a 3×3 square of cells, subtracting one-eighth of each of the outside cell values from the center cell value. The weighted average is then divided by the mean intercell distance, averaging approximately 36.2 for the 30 m DEM, and 96.6 for the 80 m DEM (Burrough 1986; McNab 1989). This yields an index value for each ground location which is a weighted average slope from the center cell to the surrounding cells. Positive values indicate the center cell is higher than surrounding cells, while negative values indicate the center cell is lower. Shape index and elevation values for each measurement plot

were derived from the cell closest to the center of each field measurement plot. Calculated terrain shape values were linearly scaled with lowest values set to 0 (highest concavity, deep coves) and highest values set to 10,000 (highest convexity, narrow, well-defined ridges). We chose a 0–10,000 range to simplify and reduce storage (positive integers) while preserving at least three significant figures for most observations. Digital elevation data were overlain with sample plot locations to estimate elevation and terrain shape for each plot. Terrain-based values were determined from each of the two digital elevation data sets, one based on 30 m USGS DEM data for the Prentiss, North Carolina quadrangle, and one based on 1-degree USGS data (approximately 80 m resolution for the study area), yielding two sets of estimates for each plot.

Relationships between vegetation and terrain data (elevation, slope, aspect, and terrain shape) were investigated. Plot data were averaged by both elevation and terrain shape intervals, to yield from 5 to 10 plots per group. Scatter diagrams of these smoothed data were plotted against each terrain variable, and trends in stem density and basal area observed. The mean locations in the terrain shape/elevation domain were plotted for samples with basal areas in the upper 50 percentile for each taxa. Selection of the upper 50th percentiles was an attempt to identify typical sites for each taxa, where a species has an above-average basal area, relative to the species norm. First- through third-order linear and log-transformed regression models were fit to the plot data, regressing basal area for each species and vegetation type against elevation, terrain shape, slope, and aspect. Linear and log-linear regressions were performed for basal area against elevation and terrain shape. Semi-variograms and correlograms were computed for each species, vegetation type, and terrain variable. Directional variation for the dependent and independent variables was assessed by estimating semi-variograms for each of the four cardinal directions and for their midpoints, and by plotting unity crossings for each direction in a rose diagram (Isaaks and Srivitstava 1989).

Vegetation maps were produced using each of four different methods. In the first method, linear regression results were applied to terrain variables mapped across the landscape. Basal area was predicted for each overstory vegetation type at each landscape cell, using independent variables derived from the 30 m DEM. Type data were then overlain to estimate total and per class basal area, and each cell assigned to a dominant vegetation type. The second method

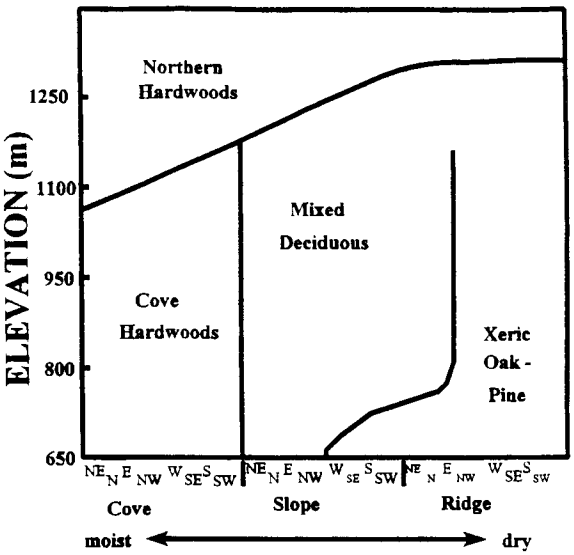

Figure 1. Typic diagram of Day et al. 1988, depicting vegetation type as a function of slope, aspect, elevation, and exposure. This diagram formed the basis for one of the mapping methods used to predict vegetation type.

used kriging models with plot data to estimate dominant vegetation type at each point on the landscape, while the third method used co-kriging models with elevation or terrain shape as the covariate. Kriging and co-kriging models were then fit, using omnidirectional spherical and gaussian models, a 15 m lag tolerance and a ± 90° angular tolerance (Isaaks and Srivistava 1989). The fourth maping method applied the mosaic diagram developed by Day et al. (1988, please see Figure 1) to map vegetation types. The mosaic diagram is a graphical representation of expected vegetation type as a function of site variables such as elevation, aspect, and topographic position. Landform, elevation, and aspect were used to assign vegetation types across the landscape. Aspect from 45° to 135°, clockwise from north was assigned an east aspect, 135° to 225° a south aspect, etc., and scaled terrain shape values < 3500 were assigned a cove landform, > 6500 assigned a ridge landform. To determine the effect of terrain data resolution on predicted vegetation types, two predicted vegetation maps were produced from this mosaic diagram, one each based on data from the 30 m and 80 m DEMs.

Vegetation classification was evaluated two ways. First, vegetation maps were visually inspected, and viewed for consistency, agreement of general trends with known environmental gradients, and the size and shape of identified vegetation polygons. In addition,

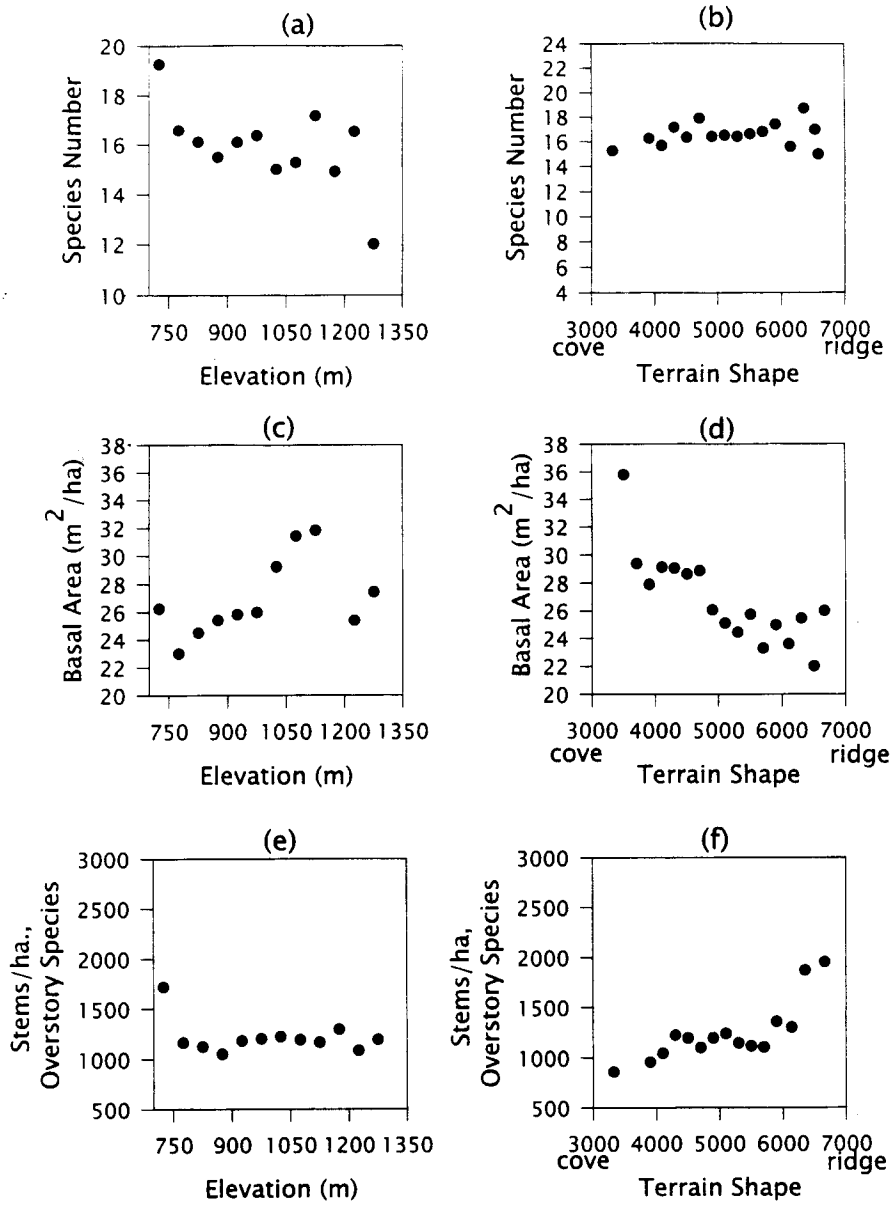

Figure 2. Scatterplot of species number, basal area, and stem density vs. terrain shape and elevation. Data are from 406, 0.08 ha plots sampled in the Coweeta Hydrologic Lab in western North Carolina. Plot values are averaged by 50m elevation type and 200 unit terrain shape class.

predicted vegetation was compared to known vegetation at each of 77 independent data points, withheld from model development and mapping. An error matrix was determined for each mapping method using these points.

Results

Stand structure, species composition, and relationships to elevation and terrain shape

Coweeta forests are diverse relative to other temperate forests (Table 1), with 11 overstory species present on over 1/2 the plots, and an average of 17 species per plot. Five species or species groups occurred on more than 80% of the plots: *A. rubrum*, *Quercus prinus*,

Carya spp., *Rhododendron spp.*, and *Oxydendum arboreum*. There were no strong relationships between any taxa and slope or aspect, so future discussions will be restricted to elevation and terrain shape, unless noted otherwise. The number of overstory species per plot was not affected by terrain shape, but did change with elevation (Figures 2a, b). We noted large variability at some levels of elevation and terrain shape, but this was not due to the smaller sample sizes at these elevations and terrain shape intervals. Simple- and log-linear regressions between elevation and species per plot were significant ($p < 0.05$, $r^2 = 0.40$ and 0.52, respectively). Similar regressions for terrain shape vs. species number were not significant. Because overstory species dominated basal area, discussions will be limited to the overstory species, unless noted. Basal area was not related to elevation (linear regression, $p > 0.1$), while there was a large, significant decrease ($p < 0.05$) in average overstory basal area as terrain shape increased (Figures 2c, d). Stem density of overstory taxa did not change with elevation, while it increased significantly with increasing terrain shape (Figures 2e, f). Taken together, these results indicate fewer species at higher elevations and more, smaller trees as one moves from coves to ridges. Taxa considered characteristic of each vegetation type (Braun 1950; Barnes 1991; Elliot et al. 1997) congregate when plotted by terrain shape and elevation (Figure 3). Taxa designated typical of coves occurred at a range of elevations, but on low terrain shape values. Northern hardwood species occurred at high elevations, xeric oak-pine species occurred on ridge sites and at low elevations, and mixed deciduous taxa occurred at intermediate elevation and terrain shape values. Some taxa occurred in high abundance over large ranges of elevation and terrain shape, e.g., *A. rubrum, Q. prinus*, and *Q. rubra*; these taxa occur at intermediate positions in Figure 3. For example, *Q. rubra* occurs between the mixed-deciduous and northern hardwood species because it occurred at above-average basal areas across a broad elevation range, and was often a significant component at lower to mid elevations. However, fewer species occurred and dominated at higher elevations, resulting in an increased prominence of *Q. rubra* on these sites.

Some species exhibited strong relationships between basal area and elevation. Species with a significant increase ($p < 0.05$, log-linear regression) in basal area with elevation include *Q. rubra, Q. prinus, N. sylvatica, A. rubrum, T. heterophylla*, and *B. lenta*. No species showed a significant negative linear response to elevation. Northern hardwood species occurred most frequently and with higher basal areas at higher elevations, although there were significant variations ($p < 0.05$) in the regression slopes among species, even within the northern hardwood community type. Simple linear and log-linear regressions indicated elevation/basal area relationships were not significant for cove or xeric oak communities. Scatter plots show highest basal areas at the highest observed elevation for some species, suggesting environmental conditions related to elevation, such as temperature or moisture, may be providing relative competitive benefit for some species (e.g., *Q. rubra* and *B. lenta)*. Other species (e.g., *Q. prinus, A. saccharum*) show apparent peaks prior to the highest elevation at which they occur. This may be because they are nearest optimum environmental conditions at a point below the highest elevation at which plots were established, or perhaps due to a bias from outliers combined with a reduced number of plots at higher elevations. Changes in basal area with elevation may also be influenced by past broad-scale disturbance. Harvesting prior to 1920 was lowest at higher elevations and ridge sites,

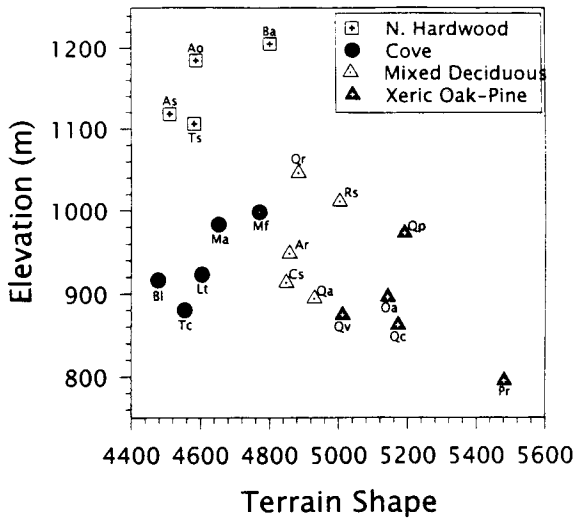

Figure 3. Mean elevation and terrain shape, by taxa. Means were based on plots where basal area was equal to or greater than average taxa basal area, to adjust for skewed basal area distrubutions, and identify conditions "typical" for each taxa. For clarity, only taxa used to define vegetation type are represented. Ao = *Aesculus octandra*, As = *Acer saccharum*, Bl = *Betula lenta*, Ba = *B. alleghenensis*, Lt = *Liriodendron tulipifera*, Qp = *Quercus prinus*, Qc = *Q. coccinea*, Qr = *Q. rubra*, Oa = *Oxydendron arboreum*, Qv = *Q. velutina*, Qa = *Q. alba*, Tc = *Tsuga canadensis*, Rs = *Robinia psuedoacacia*, Pr = *Pinus rigida* Ta = *Tilia americana*, Ma = *Magnolia acuminata*, Mf = *M. fraseri.*

Table 1. Summary basal area statistics and plot occurrence (n) for individual taxa observed.

Taxa	Mean BA (m^2/ha)	N	Std Err BA (m^2/ha)	Maximum BA (m^2/ha)
All taxa	27.1	406	0.67	117.9
Overstory taxa				
Quercus prinus	5.1	336	0.31	39.9
Q. alba	1.0	157	0.24	23.5
Q. rubra	2.8	235	0.29	26.9
Q. velutina	1.1	198	0.19	12.7
Q. coccinea	2.4	239	0.20	17.5
Q. falcata	<0.1	6	0.29	1.6
Nyssa sylvatica	1.1	339	0.08	26.6
Oxydendrum arboreum	1.3	324	0.06	6.3
Carya spp.	1.8	337	0.14	16.8
Liriodendron tulipifera	1.9	231	0.30	26.6
Robinia psuedoacacia	0.6	224	0.08	8.3
Tsuga canadensis	1.0	190	0.28	22.5
Acer rubrum	3.5	405	0.14	16.2
A. saccharum	0.1	35	0.14	2.7
Fraxinus spp.	0.1	55	0.12	4.3
Pinus rigida	0.8	84	0.41	15.4
Tilia heterophylla	0.3	48	0.51	15.5
Betula lenta	0.8	199	0.14	9.6
B. alleghaniensis	0.4	39	0.95	24.0
Fagus grandifolia	0.1	52	0.12	5.1
Magnolia fraseri	0.2	114	0.14	13.3
M. acuminata	0.1	55	0.16	4.7
Aesculus octandra	0.2	34	0.72	18.5
Prunus spp.	0.1	27	0.56	13.6
Significant understory taxa				
Rhododendron spp.	3.1	1259	329	103
Kalmia spp.	3.5	1655	264	182

although coves at most elevations were harvested. The loss of *Castenea dentata* also influenced both species number and basal area of past forests, impacts which most likely affect present forest composition and abundance.

Cove and ridge species groups were strongly related to terrain shape ($p < 0.05$, $r^2 = 0.36$ and 0.44, respectively in log-linear regressions), with cove basal area highest at low terrain shape values, and xeric oak basal area highest at with higher terrain shape values (Figure 4). Species with a significant relationship ($p < 0.05$, log-linear regression) between basal area and terrain shape include *Q. prinus, O. arboreum, L. tulipifera, T. canadensis, B. lenta, M. fraseri*, and *M. acuminata.* Basal area increased for xeric oak species and decreased for cove species at higher terrain shape index. Weak but positive and at times significant relationships to terrain shape were observed for two mixed deciduous taxa, *Q. alba* and *Carya spp.*, but there was no relationship between terrain shape and basal area for the mixed deciduous community (Figure 4). Northern hardwood and mixed deciduous basal area were not related to terrain shape and hence are not plotted.

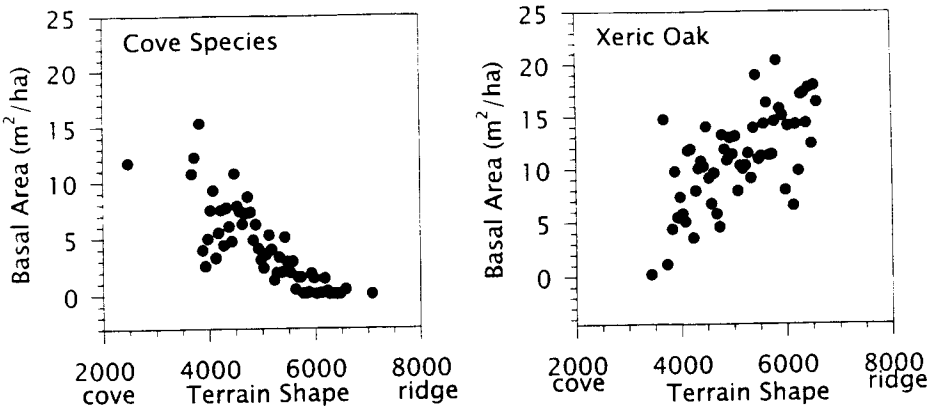

Figure 4. Basal area vs. terrain shape for each vegetation type.

Predicting vegetation composition

Semivariograms indicated relatively short-distance correlation in species composition (Figure 5). Standardized semivariograms for cove and xeric oak species groups approached unity at lag distances of approximately 100 to 150 m, indicating little association in species composition at this distance or greater. This is a typical ridge to cove distance, and most probably reflects changes in species composition associated with changes in landform. Observed maximum variabilities occurred at 150 to 200 m, and may reflect an increased likelihood of finding different terrain conditions, and hence different vegetation composition at these distances. Northern hardwood and mixed deciduous type basal areas had stronger spatial covariation, with unit standardized variation reached at approximately 400 m, reflecting a more gradual change in composition with elevation. We observed no variogram directionality, although the uniform orientation of sample transects provided larger samples and less variability for spatial covariation estimates in that direction. However, rose diagrams of individual species or vegetation type directional variograms showed no pattern, and we could not reject a hypothesis of isotropic variation.

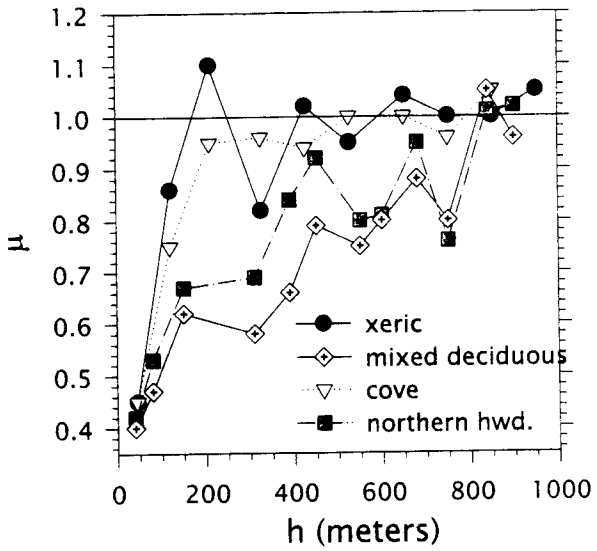

Figure 5. Standardized variogram for basal area of vegetation types defined in this study. This depicts how basal areas vary as one moves to successively more distant points. h is the lag distance, in meters between plots, while μ is the standardized among-plot variance in basal area for the community type. Measurements at adjacent points are more highly correlated than measurements at two distant points. Standardized values near 1 suggest variances as if sampled from a random population. Variograms were calculated with a ± 90° angular tolerance and a 15 m lag tolerance.

Accuracies in predicting site vegetation differ markedly, depending on the technique used (Tables 2 through 5). Mosaic diagram and linear model accuracies are similar to each other (Tables 2, 3), and higher than kriging and co-kriging accuracies (Tables 4, 5), differences which were statistically significant ($p < 0.05$, κ statistic). Somewhat surprisingly, at least for these two methods, confusion among groups was not uni- or bi-directional, i.e., no one or two group pairs had higher error rates. One might expect higher error rates for types that are typically adjacent on the landscape (e.g., for cove and mixed deciduous types, or for mixed deciduous and xeric oak). However, specific cross-type error rates are approximately equal when expressed as a proportion of the total true type. Terrain sampling frequency had a strong impact on vegetation group mapping accuracy (Table 2 vs. 6). Differences between the 30 m and 80 m sam-

pling frequency were large and statistically significant ($p < 0.05$, K statistic, Figure 6). Assignment accuracies of cove and xeric oak groups were markedly reduced at this coarse terrain sampling, indicating cove and ridge locations are not as accurately rendered from the 80 m terrain data. There was a marked increase in the identification of these two types as mixed deciduous.

Discussion and conclusions

We observed significant relationships between species basal area and terrain variables. However, species responded differently to elevation and terrain shape. Many species considered typical of a given terrain position or elevation range occurred frequently and in some abundance in other terrain conditions, e.g., *Q. rubra* was common in northern hardwoods, cove, and mixed-deciduous types, and *L. tulipifera* was abundant in both coves and sideslopes. Similarly, while *Q. prinus* was most abundant and dominant at high elevations and on ridges, it was also frequent at low elevations and at terrain shape values characteristic of toe-slopes and coves. *A. rubrum* was found in high abundance across a broad range of both elevations and terrain shapes. Our results suggest that southern Appalachian forest species and communities change in concert with elevation and an index of terrain shape, but there is great variability in the species mix and abundance within each community type, and a great deal of overlap in the types.

Average plot basal area decreased from cove to ridge, and stem density increased. Smaller average diameters may be due to a number of factors. Quantitative relationships among species and terrain in this region may be confounded by the variety of past land use practices that varied temporally and spatially, and also by past natural disturbances, such as windthrow and the loss of *Castanea dentata* (Nelson 1955; Stephenson 1974; Woods and Shanks 1959; Lorimer 1980). Another factor may be slower growth on ridge sites. Most of the basin was selectively logged in the decade prior to 1923, and if disturbance intensity was similar on ridges and in coves, faster growth in coves would lead to larger average diameters and lower density through earlier self-thinning. However, because it was a diameter limit cut, and because the stand access was through a valley-bottom road network, coves may have been more heavily cut, particularly at lower elevations. Ridge forests may be advanced in age, and more likely to suffer stand-replacing disturbances (Runkle 1982). Finally, even if stands were not mature, drought intensity, windthrow, or other disturbances may be more severe and frequent as one moves from coves to ridges (Meiners et al. 1984). This, coupled with slower growth rates on ridges, results in more trees, with a smaller average diameter.

We observed some species to be weakly or unrelated to terrain shape and elevation. *Q. coccinea, Q. velutina, R. psuedoacacia, B. alleghaniensis*, and *A. saccharum* were not significantly related to terrain variables. The last two species were represented by small sample sizes, reducing our ability to determine relationships. The remainder may be species which are generally adaptable across a range of conditions, but do not dominate. *Q. coccinea* and *Q. velutina* are typically of dry slopes and ridgetops, however they both occur in toe- and sideslope locations at proportions nearly as high as on ridges. Spatial variation in disturbance, when accumulated across longer time scales, may provide opportunities for these species to remain in the canopy across a range of terrain conditions (Lorimer 1980; Meiners et al. 1984).

Fire suppression may also be affecting species composition and distribution (Garren 1943). Rhododendron has a documented influence on reproduction and species composition in southeastern U.S. deciduous forests (Phillips and Murdy 1985), through both light absorption, litter accumulation, and perhaps competition for below-ground resources. However rhododendron is slow-growing, and after fire many overstory species may become established before rhododendron stump sprouts can fully re-occupy a site. *A. rubrum* and *Rhododendron spp.* were among the most frequent and dominant overstory and understory taxa observed. Both taxa are fire intolerant and shade tolerant, and our results are consistent with posited increases in these species due to fire suppression.

We observed little difference between mosaic diagram and the terrain-based linear models in predicting overstory vegetation types. This may reflect accuracy in the mosaic diagram, which was developed by plant ecologists working at Coweeta (Day et al. 1988). It incorporates the relationships between species type, topographic position, aspect, and elevation in a succinct form, and although not based on the same set of observations as the present study, is from work in the same area. Because it was locally developed however, we cannot determine the generality of this mosaic diagram. Similarity in the results of the linear model

Table 2. Error/accuracy table for withheld test points, log-linear model to predict vegetation type basal area, with 30 m terrain sampling. Column sums are the number of test points in each vegetation type, diagonal elements are correctly mapped, and off-diagonal elements are errors in classification.

Predicted vegetation	Northern hardwood	True Vegetation: Mixed deciduous	Xeric Cove	oak/pine	Row sum
Northern hardwood	5	4	2	2	13
Mixed deciduous	2	16	8	4	30
Cove	1	6	14	0	21
Xeric oak/pine	1	2	1	9	13
Column sum	9	28	25	15	Correct 57%

Table 3. Error/accuracy table for withheld test points, typic diagram of Day et al. (1988), with 30 m terrain sampling.

Predicted vegetation	Northern hardwood	True Vegetation: Mixed deciduous	Cove	Xeric oak/pine	Row sum
Northern hardwood	8	4	4	2	18
Mixed deciduous	1	17	9	7	34
Cove	0	4	11	1	16
Xeric oak/pine	0	3	2	6	11
Column sum	9	28	25	15	Correct 55%

and mosaic diagram methods may also be caused by the relatively broad vegetation types chosen, and the methods may diverge as accuracies degrade for finer sets of types.

Our work indicates terrain sampling frequency has a significant impact on vegetation maps. Vegetation maps based on 80 m terrain sampling were significantly less accurate than those based on a 30 m sampling frequency, at least when using the mosaic diagram. This reduction in accuracy may be due to mis-classification in terrain shape when using the larger sampling interval. Blaszczynski (1997) noted differences in landform classification related to kernal size, with less distinction between concave and convex sites at coarser samplings. Mis-classified landform would quite often lead to mis-classified vegetation classes. Part of the classification error may also be associated with increased positional mis-registration. Measurement plots were 20 m by 40 m. The expected 7 m positional accuracy for the 30 m DEM would yield a majority of most measurement plots falling within the correct DEM cell. However, a comparable proportional accuracy of approximately 19 m for the 80 m DEM would result in a larger proportion of the measurement plots falling in neighboring or further removed DEM cells. In addition, registration accuracy is likely to be proportionally worse for the 80 m DEM (USGS 1980), resulting in yet larger offsets. This, coupled with greater generalization at the coarser sampling, may have caused the deterioration in terrain/vegetation modeling. We did not exhaustively analyze the effect of horizontal sampling frequency on terrain position identification or vegetation mapping accuracy. However, we posit a threshold resolution somewhere between 30 and 80 m, related to regional terrain conditions and geologic history where there is a nonlinear decay in prediction accuracy, and we are currently developing field and digital elevation sampling data to test these hypotheses, and to further develop indices of terrain shape. If other properties vary along with terrain position and vegetation type, e.g., biomass, carbon cycling, or nutrient cycling, then

Table 4. Error/accuracy table for withheld test points, ordinary kriging, 30 m terrain sampling.

Predicted vegetation	True Vegetation				
	Northern hardwood	Mixed deciduous	Cove	Xeric oak/pine	Row sum
Northern hardwood	3	1	3	0	7
Mixed deciduous	0	11	8	2	21
Cove	0	1	4	0	5
Xeric oak/pine	0	11	8	11	13
Column sum	3	24	23	13	Correct: 44%

Table 5. Error/accuracy table for withheld test points, co-kriging, 30 m terrain sampling.

Predicted vegetation	True Vegetation				
	Northern hardwood	Mixed deciduous	Cove	Xeric oak/pine	Row sum
Northern hardwood	2	2	3	0	7
Mixed deciduous	0	13	10	3	26
Cove	0	3	4	0	7
Xeric oak/pine	0	8	5	8	21
Column sum	2	26	22	11	Correct: 46%

analyses based on these larger sampling frequencies may contain significant errors. Many landscape, regional, or global studies generalize vegetation and terrain variables at this 80 m resolution or higher, for example at 500 m to 1000 m or larger (Ågren et al. 1991; Aber et al. 1993). An important question for each of these studies is how the processes modeled or analyzed are affected by subgrid terrain-related changes in species composition, basal area, stem density, or biomass. Vegetation characteristics appear to vary predictably over terrain, and if this causes "large" differences in the process of interest, e.g., below-ground allocation or differences in plant tissue respiration rates, then fine-scale sampling and modeling (30 m or less) may be warranted.

We conclude that kriging and co-kriging are not useful for mapping forest type and species composition in the southern Appalachians, at least when applied at the scales and sampling frequencies investigated. These methods suffer from at least two drawbacks which limit their utility for vegetation mapping at broad scales. First, spatial covariation decreases rapidly with distance, particularly for species typical of cove and ridge positions. Little may be inferred from a given field plot, where overstory basal area and species composition are measured, to points more than 100 m distant. This requires denser plot sampling than is typical of most vegetation mapping projects. In addition, geostatistical techniques are best when restricted to mapping within the convex hull of the sample points, requiring more complete sampling around the periphery of the study region. Finally, mapping accuracies based on these two techniques are lower than the terrain-based model and mosaic diagram methods.

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Table 6. Error accuracy table for withheld test points, typic diagram of Day et al. (1988), with 80 m terrain sampling

Predicted vegetation	Northern hardwood	True Vegetation: Mixed deciduous	Cove	Xeric oak/pine	Row sum
Northern hardwood	5	3	3	1	12
Mixed deciduous	1	14	13	10	38
Cove	2	8	5	1	16
Xeric oak/pine	1	3	4	3	11
Column sum	9	28	25	15	Correct: 35%

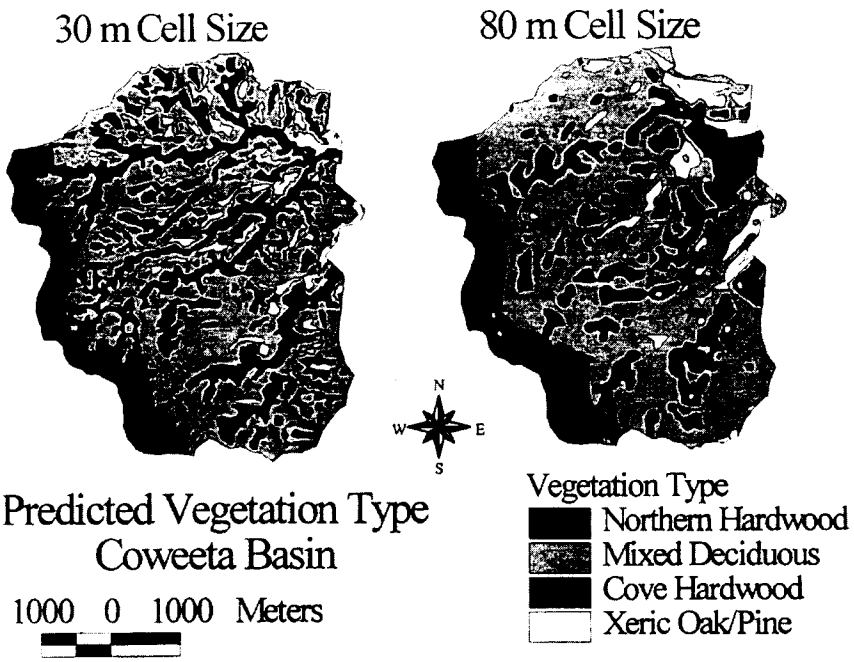

Figure 6. Vegetation maps developed from the typic diagram, using digital elevation data with either 30 m or 80 m DEM resolution.

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