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Ecological Zones in the Southern Appalachians: First Approximation

Steve A. Simon, Thomas K. Collins,
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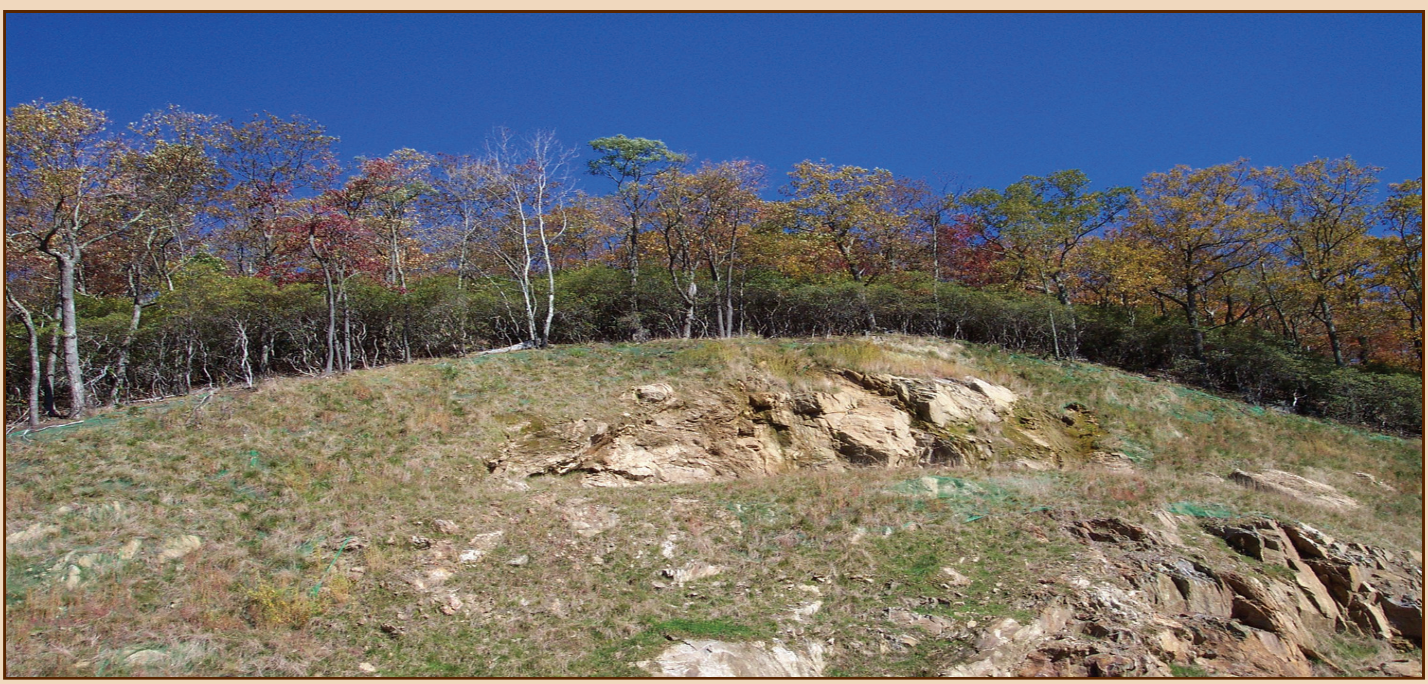

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Cover Photos

Ecological zones, regions of similar physical conditions and biological potential, are numerous and varied in the Southern Appalachian Mountains and are often typified by plant associations like the red spruce, Fraser fir, and northern hardwoods association found on the slopes of Mt. Mitchell (upper photo) and characteristic of high-elevation ecosystems in the region.

Sites within ecological zones may be characterized by geologic formation, landform, aspect, and other physical variables that combine to form environments of varying temperature, moisture, and fertility, which are suitable to support characteristic species and forests, such as this Blue Ridge Parkway forest dominated by chestnut oak and pitch pine with an evergreen understory of mountain laurel (lower photo).

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Abstract

Forest environments of the Southern Appalachian Mountains and their characteristic plant communities are among the most varied in the Eastern United States. Considerable data are available on the distribution of plant communities relative to temperature and moisture regimes, but not much information on fertility as an environmental influence has been published; nor has anyone presented a map of the major, broad-scale ecosystems of the region, which could be used for planning and management of biological resources on forestlands. Our objectives were to identify predominant ecological units, develop a grouping of geologic formations related to site fertility, and model and map ecological zones of the Southern Appalachians. We synthesized 11 ecological units from an earlier analysis and classification of vegetation, which used an extensive database of over 2,000 permanent, 0.10-ha, intensively sampled plots. Eight lithologic groups were identified by rock mineral composition that upon weathering would result in soils of low or high availability of base cations. The presence or absence of ecological zones (large areas of similar environmental conditions consisting of temperature, moisture, and fertility, which are manifested by characteristic vegetative communities) were modeled as multivariate logistic functions of climatic, topographic, and geologic variables. Accuracy of ecozone models ranged from 69- to 95-percent correct classification of sample plots; accuracy of most models was > 80 percent. The most important model variables were elevation, precipitation amount, and lithologic group. A regional map of ecological zones was developed by using a geographic information system to apply the models to a 30-m digital elevation dataset. Overall map accuracy was refined by adjusting the best probability cut levels of the logistic models based on expert knowledge and familiarity of the authors with known ecological zone boundaries throughout the study area. Preliminary field validation of an uncommon fertility-dependent ecological zone (Rich Cove) indicated a moderate, but acceptable level of accuracy. Results of this project suggest that bedrock geology is an important factor affecting the distribution of vegetation. The developed map is a realistic depiction of ecological zones that can be used by resource managers for purposes ranging from broad-scale assessment to local-scale project planning.

Keywords: Classification, ecosystems, fertility, geologic formations, logistic regression, moisture, multivariate analysis, ordination, temperature.

Introduction

The Appalachian belt of mountain ranges, which extends from Alabama to Labrador, is among the oldest and most weathered in Eastern North America. The Southern Appalachian portion, extending from northeast Georgia to central Virginia, is a relatively narrow [10 to 100 km (6 to 60 miles) wide] region of forested, broadly rounded mountain peaks separated by wide U-shaped valleys (fig. 1). Altitudinal climatic zonation, complex topography, and a humid, temperate climate form some of the most diverse natural environments in the Eastern United States (Braun 1950, Pittillo and others 1998, Schafale and Weakley 1990). Its varied climate, geology, and soils provide a range of habitats suitable for approximately 2,250 species of vascular plants (Southern Appalachian Man and the Biosphere 1996). About 70 percent of this region is forested and 12 percent is in Federal ownership as national forests and parks (Southern Appalachian Man and the Biosphere 1996). Public lands, particularly national forests, long have been managed for multiple uses, but timber production traditionally has been emphasized to meet local and regional economic needs. However, the economies of many communities have changed to meet increased demands for services from growing urban populations and visitors who view the forested landscape as more valuable for biological conservation and recreation than for timber production. Accordingly, U.S. Department of Agriculture Forest Service (Forest Service) policy has evolved toward ecosystem management, which requires consideration of physical, biological, and cultural components of forested sites and landscapes (Rauscher 1999).

To assist managers and planners in implementing ecosystem management policies, a hierarchical framework of ecological units has been developed (Cleland and others 1997), maps of large regional ecosystems (ecoregions) in the United States have been delineated (Bailey and others 1994, Keys and others 1995), and generalized vegetation of those ecosystems has been described (Bailey 1995, McNab and Avers 1994). Hierarchical ecological delineations attempt to integrate successively smaller, homogeneous combinations of climatic, geologic, and biological components, which determine the overall biotic potential of an area (Kimmins 1987). Mapping of ecological units has been done mostly at broad national and regional scales using expert knowledge, subjective stratification of ecoregions, and qualitative integration of important environmental features (Host and others 1996). However, identification of units at a landscape scale is necessary for project planning (Cleland and others 1997). Logically, delineation of small ecosystem units should be based on field data that allow quantitative grouping of sites

Figure 1—Typical low-elevation forested landscape of the Southern Appalachian Mountains south of Asheville in the Pisgah National Forest where evergreen shrubs along ridges form a recurring pattern of vegetation associated with landform. The Blue Ridge Mountains on the horizon define the escarpment leading down to the Appalachian Piedmont.

where temperature, moisture, and fertility attributes form environments with similar ecological characteristics. Such units could be expected to respond predictably to natural disturbance or management activities.

Different Southern Appalachian environments and patterns of distinctive vegetation long have been described, but early investigations were largely subjective and descriptive (Cain 1931, Harshberger 1903). However, Davis (1930) did report major vegetative associations in the Black Mountains using Livingston atmometers to quantify evaporation (McLeod 1988, p. 150). Later studies were more objective, describing the relationship of vegetation to environment using field plot data (Whittaker 1956). More recently, multivariate methods of classification and ordination have been used to describe the mathematical relationships of vegetation and environment (DeLapp 1978, Golden 1974, McLeod 1988, McNab and others 1999, Patterson 1994[1]). Although many intensive ecological investigations have been conducted in the Southern Appalachians, most have used a restricted scope of study, such as being confined to a portion of a mountain range (McLeod 1988[1]), a watershed (Newell and Peet 1998[2]), or a particular vegetation type (DeLapp 1978, White and others 1984, Wiser and others 1998). One exception was the work of Newell and others (1999), in which data from five widely separated locations in the Southern Appalachians were combined in a meta-analysis to examine environmental factors influencing the regional distribution of vegetative communities. Most small-scale studies concluded that vegetative community composition primarily was influenced by temperature regimes, then by moisture availability; the large-scale study of Newell and others (1999) reported that soil nutrient levels are also an important factor affecting the distribution of vegetation across a landscape.

The relatively narrow geographic or ecologic scope of many studies fails to consider broader regional questions, such as ecosystem distribution and species interactions, which may be important when evaluating species rangewide viability and when trying to achieve consistency in ecosystem

[1] Ulrey, C.J.; McLeod, D.E. 1992. Preliminary summary of the biodiversity study of the vegetation in the Craggy Mountains, Pisgah National Forest, Toecane District, North Carolina. 13 p. Unpublished report. On file with: U.S. Department of the Interior, Blue Ridge Parkway, 199 Hemphill Knob Road, Asheville, NC 28803.

[2] U.S. Department of Agriculture Forest Service. Ecological classification, mapping, and inventory for the Chattooga River watershed. 500+ p. Unpublished draft report. On file with: USDA Forest Service, National Forests in North Carolina, P.O. Box 2750, Asheville, NC 28802.

management (Host and others 1996). The differing objectives, methods, data collection, and analyses among studies do not allow pooling results for a larger, meta-analysis of region-wide datasets or objective development of a regional map of ecosystems.

Ecosystems in the Southern Appalachians have been subjectively delineated through successive stratification of regional-scale map units using a hierarchical framework (Keys and others 1995). Boundaries of these broadly delineated ecosystems lack detail necessary for resource management purposes other than planning and assessment. Ecological units derived through analysis of field data would provide a means of refining boundaries of the large units and perhaps allow derivation of smaller units that nest within the hierarchy.

A subregional, hierarchical vegetation classification developed by Ulrey[3] could provide a basis for stratifying the Southern Appalachians on an ecological basis. That classification identifies units of compositionally similar vegetation for the purpose of inventory and management. Ulrey[3] wrote that "Ideally, these compositionally similar vegetation units will also be environmentally similar as well, but this report does not address this issue." The classification was made using 18 datasets compiled from over 2,000 sample plots, which had been installed to determine species composition and abundance, and associated environmental attributes. Numerical classification and ordination analyses resulted in tentative identification of a hierarchy of vegetation units consisting of 3 major vegetation groups, 13 ecological groups, and 35 ecological subgroups. Use of this classification system for regional ecological stratification is possible because easily quantified topographic variables, i.e., elevation and landform, are correlated with two primary environmental factors (temperature and moisture), but similar variables are not available for fertility. Subsequently, Newell and others (1999) and Ulrey (2002) reported that soil chemical properties were associated with fertility. However, soil maps generally do not provide a means of application of those findings because soil taxonomic units are based more heavily on physical features of the soil profile than on chemical properties. As an alternative to soil maps, Robinson[4] suggested that mapped bedrock formations could be used to account for the variation in availability of soil cations that typically are associated with soil fertility.

Geology of the Southern Appalachians has been studied extensively in an effort to explain the origin, arrangement, and current structure of various bedrock formations (Hack 1982, Hatcher 1988, King and others 1968). Formation types are diverse and range from old, highly metamorphosed Precambrian Blowing Rock gneiss in the Grandfather Mountain window to younger, relatively little-changed Devonian quartz diorite of Whiteside Mountain granite (North Carolina Geological Survey 1985). Few studies, however, have included rock units as an ecological component that potentially affects vegetation composition and distribution. Zobel (1969) found that the occurrence of Table Mountain pine (see appendix E for scientific names of species) appeared to be associated more with the physical features of landforms formed by weathering of certain geologic formations, than with the chemical composition of the rocks. Working in the Pilot Mountains of North Carolina, Rohrer (1983) reported that vegetation types were related to rock type. In the mountains of northeast Georgia, Graves and Monk (1985) found flora differed significantly on adjacent gneiss and limestone rock types. In a regional study of Southern Appalachian vegetation present on rock outcrops, Wiser and others (1996) found that soil nutrients were associated with the underlying rock chemistry, and they explained significant variation in the species composition of herbaceous and shrub communities. In comparison with moisture and temperature-related environmental components, relatively little current information allows grouping of rock types for ecological applications, such as Whiteside's (1953) matrix approach for stratifying formations by texture and fertility soil properties.

Few ecological investigations have resulted in quantitative models for predicting the occurrence and distribution of ecoregions in the Southern Appalachian Mountains. McNab (1991) used multiple discriminant analysis to model the distribution of four forest types based on topographic variables in a small watershed. Fels (1994) used individual multiple regressions based on topographic variables to model distribution of 27 species and 5 communities in the Ellicott Rock Wilderness of northeastern Georgia. In an ecological classification of the Chattooga River, multiple discriminant analysis was used to model the landscape distribution of 17 environment-vegetation units (see footnote 2). Wiser and others (1998) found that multiple logistic regression performed well in predicting the occurrence of plant communities on rock outcrops. However, such analytical methods do not allow consideration of judgment or expert knowledge in the modeling process, which may help overcome limitations of imperfect mathematical models based on inadequate datasets (Mora and Iverson 2002).

[3] Ulrey, C.J. 1999. Classification of the vegetation of the Southern Appalachians. Report to the USDA Forest Service, Asheville, NC. 88 p. Unpublished report. On file with: Southern Research Station, Bent Creek Experimental Forest, 1577 Brevard Road, Asheville, NC 28806. (Available on CD-ROM inside the back cover.)

[4] Robinson, G.R., Jr. 1997. Portraying chemical properties of bedrock for water quality and ecosystem analysis: an approach for New England. U.S. Geological Survey Open-File Rep. 97–154. 11 p. On file with: U.S. Department of the Interior, U.S. Geological Survey, 903 National Center, Reston, VA 20192.

The overall purpose of our study was to investigate and quantify the composition and distribution of vegetation relative to environments in a portion of the Southern Appalachian Mountains. Our specific objectives were to: (1) adapt the vegetation classification developed by Ulrey (see footnote 3) to provide a framework of hypothesized ecological units, (2) devise a classification of geologic formations in relation to soil fertility, (3) develop mathematical relationships among vegetation groups and their associated environmental attributes to formulate ecological zones, and (4) devise a method of applying models of ecological zones with a geographic information system (GIS) that allows integration of expert knowledge. Our study primarily was an exploratory analysis; in it we observed vegetation composition and correlated environmental variables with minimal confirmation of results. Therefore, we do not provide coefficients of the prediction models that would allow users to develop customized maps of ecosystems.

We provide definitions of several terms that are important in our study. The physical environment of a site inhabited by a plant community consists of the inorganic components associated with heat, water, and nutrients. Plant community is defined following Schafale and Weakley (1990): "a distinct and reoccurring assemblage of . . . plants . . . and their physical environment." This definition of plant community is similar to that used in the national vegetation classification system (Grossman and others 1998): "Assemblages of [plant] species that co-occur in defined areas at certain times . . . ." Ecological zone is defined as a relatively large area of generally similar environmental conditions of temperature, moisture, fertility, and disturbance. One or more types of disturbance, e.g., ice, wind, drought, and fire, are typically associated with ecological zones (White 1979); but the scope of our study did not allow investigation of this ecosystem component. Supplemental information on autecological relationships, which was the basis of our study on the distribution of plant species along environmental gradients, can be obtained from forest ecology texts by Kimmins (1987), Spurr and Barnes (1973), and other authors.

Methods

Study Area

The study area consists mainly of the mountainous region of western North Carolina, an area of about 2.2 million ha (5.6 million acres) that extends in a southwest-northeast direction from latitude 35° (near Murphy) to 36.5° (near Jefferson) and from longitude 81° to 84° (fig. 2). It ranges in width from about 80 km (50 miles) in the north to about 160 km (100 miles) in the south. Its boundary follows the crests of several mountain ranges on the west side, and in the east grades into the hilly terrain of the Appalachian Piedmont. It also includes small areas of the Great Smoky Mountains National Park in eastern Tennessee, and the Chattooga River Basin in northeastern Georgia and northwestern South Carolina. Geologists refer to this region as the southern Blue Ridge Mountains (Hack 1982). Braun (1950) includes the study area in a larger region she called the Southern Appalachians, which extends from Roanoke Gap, VA, to Dalton, GA. Small-scale ecoregion mapping by the Forest Service places this area in three units: (1) central Blue Ridge Mountains, (2) southern Blue Ridge Mountains, and (3) metasedimentary mountains subsections of the Blue Ridge Mountains section (Keys and others 1995).

The region's climate is characterized as modified continental, with warm summers and cool winters. Mean annual temperature varies only slightly from north to south, ranging from 10.8 °C (51.4 °F) at Jefferson [844 m (2,777 feet) elevation; 36°25′ N., 81°26′ W.] to 13.2 °C (55.8 °F) at Murphy [500 m (1,645 feet) elevation; 35°07′ N., 84°00′ W.]. Precipitation and temperature generally increase from north to south (fig. 3). Within the study area, recorded precipitation ranges from a low of 96.5 cm (38 inches) at Asheville [683 m (2,247 feet) elevation] to 231 cm (91 inches) at Lake Toxaway [933 m (3,060 feet) elevation] (fig. 4). These two locations are only about 64 km (40 miles) apart, but precipitation is strongly influenced by prominent topographic features of the Asheville Basin and the Blue Ridge Escarpment. A conspicuous large area of particularly high interpolated precipitation occurs west of Brevard along the crest of the Balsam Mountains. Most summer precipitation results from thunderstorms associated with maritime weather patterns that are influenced by the Gulf of Mexico; winter precipitation results from continental weather systems. Generally, precipitation is evenly distributed during the year with no pronounced dry or wet seasons, although winter precipitation tends to be considerably higher in the southern part of the study area.

Relief of the study area is characterized by discrete ranges of relatively high mountains with rounded peaks that are separated by broad, somewhat hilly intermountain basins (fig. 5). Elevation ranges from 500 m (1,640 feet) at Murphy to 2038 m (6,684 feet) at Mt. Mitchell, the highest point in the Eastern United States. Relief is steep throughout much of the study area, averaging more than 50 m (165 feet) in a 6-km^2 (2.3-square mile) area (Hack 1982). Landscape-scale landforms of mountain ranges comprise a recurring pattern of secondary and tertiary ridges separated by narrow valleys that usually contain perennial streams. Large floodplains are restricted to low-gradient rivers and large streams of the intermountain basins. The varied gently rounded relief of

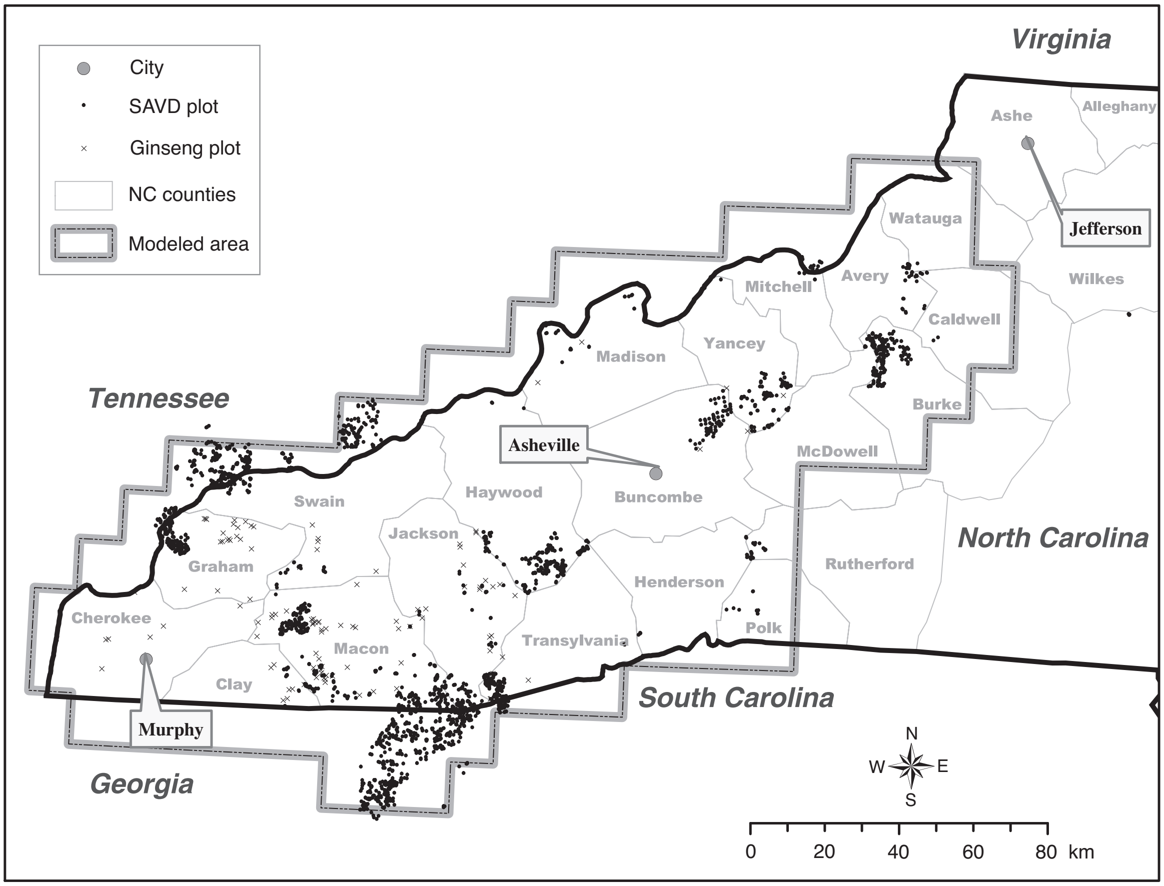


Figure 2—Location of sample plots in the Southern Appalachian vegetation dataset (SAVD).

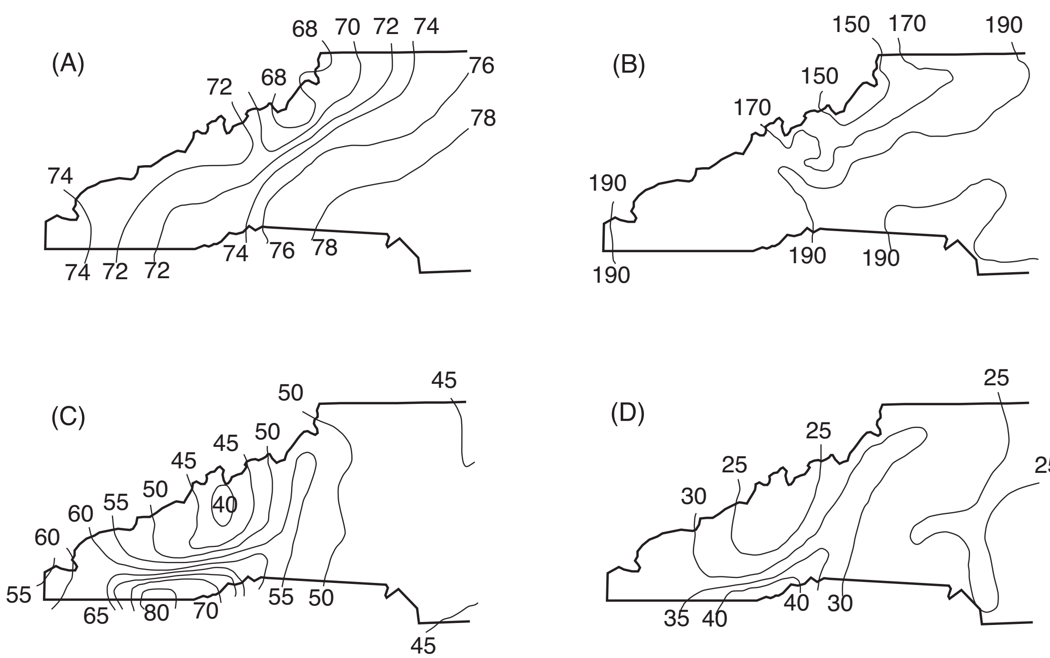


Figure 3—Temperature and precipitation variation in the study area: (A) average July temperature (° F), (B) average number of days without killing frost, (C) average annual precipitation (inches), (D) average warm-season precipitation (inches). [Adapted from U.S. Department of Agriculture (1941)].

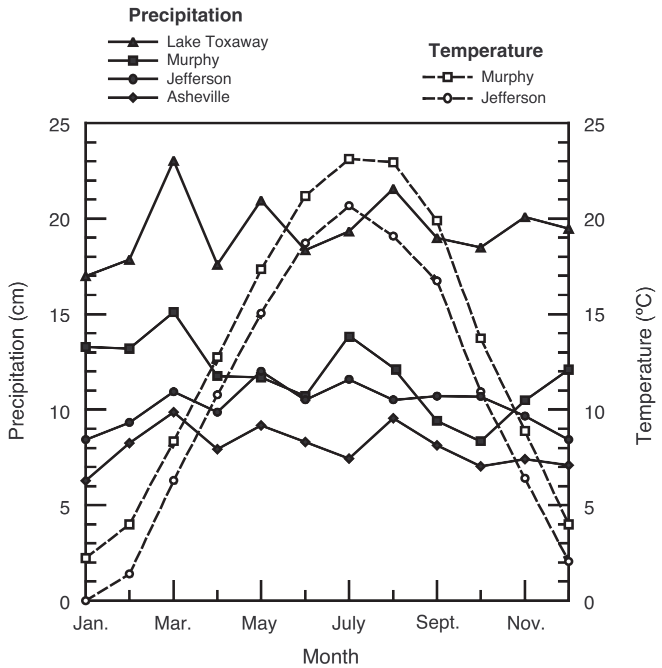


Figure 4—Monthly normal (1961–90) precipitation and temperature in the northern (Jefferson) and southern (Murphy) parts of the study area and precipitation at stations of the lowest (Asheville) and highest (Lake Toxaway) annual amounts.

the study area is primarily attributable to a combination of warm, humid climate and geologic formations of differing resistance to erosion, which has been occurring for about 300 million years during a relatively long period of geologic stability with no mountain-building episodes (Hack 1982, Pittillo and others 1998).

Geologic formations of the study area are among the oldest, most complexly arranged, and compositionally varied in the Eastern United States. Most have undergone one or more periods of metamorphosis, during which the original rocks were weathered and eroded into components that were transformed to other rock types by varying degrees of heat and pressure, making accurate age determination doubtful (Hatcher 1972). Generally, formations of the Blue Ridge Province are primarily metasedimentary types with lesser areas of sedimentary and intrusive rocks. They are arranged in six relatively distinctive northeast-southwest trending belts of varying width, extent, and age (fig. 6) (North Carolina Geological Survey 1991). From east to west, the first belt, in the southeastern part of the study area bordering the Appalachian Piedmont, consists of intrusive rocks of uneven-grained monzonitic to granodiorite gneiss with large, exposed outcrops of moderately to weakly foliated granites. Next to the west, the narrow and highly linear Brevard fault zone is a relatively young, narrow belt of schist, marble,

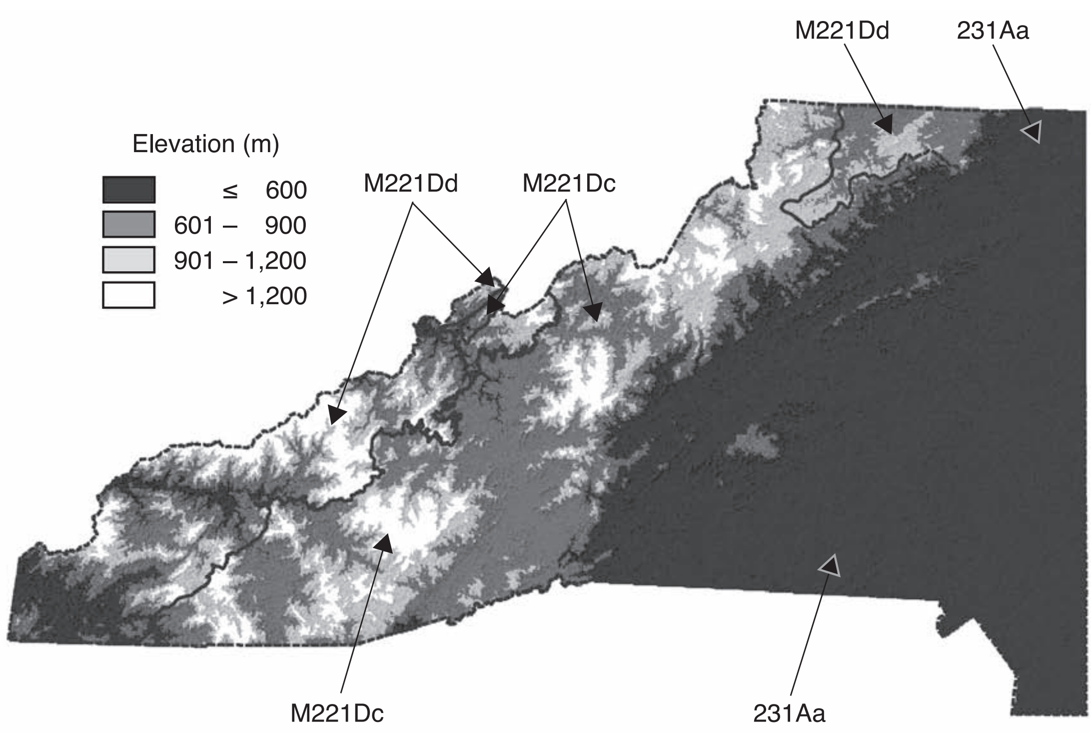
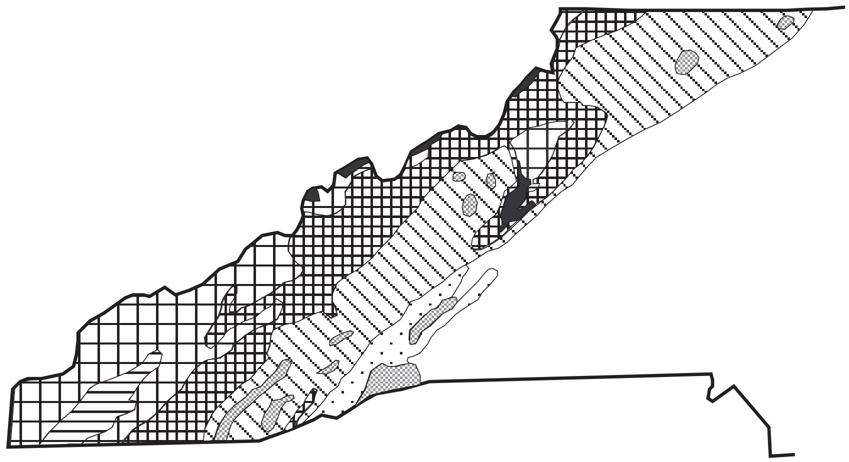


Figure 5—Topographic relief of the study area overlaid with subregional ecological units (Keys and others 1995).



Sedimentary and metamorphic rocks

Late Proterozoic to early Paleozoic age

- Sedimentary

Late Proterozoic age

- Clastic and carbonate metasedimentary
- Clastic metasedimentary and metavolcanic
- Clastic metasedimentary rock, and mafic and felsic metavolcanic rock

Middle Proterozoic age

- Felsic gneiss derived from sedimentary and igneous rocks in the northern area, biotite gneiss in the southern area

Intrusive rocks

Late Proterozoic to middle Paleozoic age

- Metamorphosed granitic rocks
- Metamorphosed gabbro and diorite

Figure 6—Generalized geologic formations of the study area (North Carolina Geological Survey 1991).

and phyllonite that marks the last major episode of geologic activity. The third belt, which is the largest and most extensive, consists of clastic gneiss, schist, metagraywacke, amphibole, and calc-silicate granofels. Occurring within this belt are scattered areas of intrusive quartz diorite to granodiorite formations. This belt is discontinuous and is separated about midway by a large area of varied rocks including metavolcanic types of the Grandfather Mountain window, gneiss basement rocks, and siltstones and shales. The fourth belt, also extensive, consists of felsic gneisses derived from sedimentary and igneous rocks that are variably interlayered with amphibolite, calc-silicate granofels, and rare marble. Occurring next, in the southwest mainly, are clastic metasedimentary, metavolcanic, and quartzite with slate, metasiltstone, metagraywacke, and calc-silicate granofels. Finally, bordering Georgia, the Murphy Belt is a small area of carbonate metasedimentary rocks that includes units of schist, phyllite, quartzite, marble, slate, and metasiltstone. Most geologic formations in the study area weather to form soils of acidic reaction. However, localized areas of hornblende gneiss are present throughout, which weathers to produce soils of less acidity. Rock formations range in age from middle Proterozoic (1 billion years) to Permian (250 million years), but age is less important than rock mineral content and texture in determining soil properties that can influence plant species composition.

Most soils of this region are classified as Ultisols (primarily Hapludults) or Inceptisols (mainly Dystrochrepts) (Pittillo and others 1998). Entisols are uncommon and seem to be found only in sandy, new alluvium of larger streams and rivers, and in colluvium of recent landslides. Hapludults generally are formed in stable parent material on gentle-to-moderate slopes and typically have little clay (< 15 percent) in their A horizon, but have high accumulation in their B horizon. Productivity of most Hapludults is low due to a combination of low base saturation (< 35 percent) and organic matter content, high acidity, and clayey subsoils on convex land surfaces that can dry quickly during the growing season with lack of precipitation and high-evapotranspiration rates. Dystrochrepts typically are present on steep slopes, or in colluvium, and have a loamy texture (average of 20 percent clay, 30 percent silt, and 50 percent sand) throughout their profiles. Productivity is moderate for these soils due to generally higher moisture and organic matter contents. Alluvial soils are typically Inceptisols and vary in productivity depending mainly on texture and organic matter content. The temperature regime of soils on landscapes below about 1372 m (4,500 feet) is classified as mesic; above that elevation soils are generally frigid. The moisture regime of upland soils is classified as udic, indicating that plant growth is not limited by lack of moisture during most years. Most soils are deep [> 100 cm (> 40 inches)]. Soil mapping units in the mountainous terrain of the study area are highly correlated with altitude, geologic substrate, and topography (Pittillo and others 1998).

Soil pH influences species composition in the Black Mountains and Craggy Mountains of the Southern Appalachians by affecting fertility, e.g. nutrient availability (McLeod 1988). Most upland soils are strongly acid (pH 4.5 to 5.5) and low in fertility, except where the parent material consists of carbonate or mafic rock formations. Mafic formations contain greater amounts of basic minerals, e.g., horneblende gneiss, which can form soils with higher pH and greater availability of nutrients. Higher fertility levels also can result from nutrient enriched subsurface flow of water from upper slopes to lower slopes (Pittillo and others 1998). Newell and others (1999) found that soil fertility regimes based on levels of manganese, instead of other conventional measures, were an important environmental component explaining the distribution of forest community classes in a large regional study of vegetation.

About 2,250 species of vascular plants occur in the Southern Appalachians (Southern Appalachian Man and the Biosphere 1996). Of the 140 tree species, most are deciduous hardwoods; only 10 are conifers. Several dozen shrubs are present. Forest cover type is predominantly oak-hickory, although areas with high proportions of conifers occur throughout (fig. 7). Elevation strongly influences vegetation composition and may be grouped into three broad zonal bands of altitude: (1) low, < 671 m (2,200 feet); (2) middle, from 671 to 1372 m (2,200 to about 4,500 feet); and (3) high, over 1372 m (4,500 feet). Low-elevation ecosystems include many of the major intermountain basins, such as the Asheville Basin, where several hardwood species more typical of Piedmont forests occur, e.g., southern red oak, including a high proportion of yellow pines. A hardwood-pine mixture is prevalent in the southwest part of the study area near Murphy, NC, and along portions of the Blue Ridge Escarpment and several other areas, particularly where soils are derived from granitic formations. Floodplain forests are uncommon and generally are restricted to the low-elevation intermountain basins, which also contain much of the human population and, consequently, are highly disturbed. Middle-elevation forests occur on moderate-to-steep mountain slopes. Xeric-to-submesic sites are dominated by five oak species, a midstory stratum of shade-tolerant trees, and often an understory of mainly evergreen (Ericaceae) shrubs. The overstory of valley and cove sites of middle elevations is dominated by mesic species, including yellow-poplar and occasionally northern red oak. In the high-elevation zone, northern red oak dominates warm slopes and ridges and nonoak deciduous species common to northern latitudes increase in importance on colder, north-facing slopes. Forests above about 1677 m (5,000 feet) become gradually dominated by red spruce and above 1830 m (6,000 feet) by Fraser fir. Except at the highest elevations, red maple occurs throughout.

With few exceptions, the range of most vegetative species sampled extends throughout the study area. Stands of red spruce and Fraser fir generally are absent south of the Balsam Mountains (35°15′), which may be a result of the lack of high-elevation habitats. Bear huckleberry does not occur north of the Asheville Basin. Several herbaceous species, including common stonecrop and northern bush honeysuckle, are absent or rare in the southern part of the study area.

Natural disturbance to forests in the study area occurs mainly from drought, ice storms, and occasionally wind from remnants of tropical hurricanes. Isolated, usually small areas [< 0.4 ha (< 1 acre)] of wind-thrown trees occur from downbursts associated with thunderstorms, mainly during the summer growing season. Natural fires are uncommon, but may occur from lightning strikes during early spring or late fall. Other minor sources of disturbance result from debris slides associated with steep, unstable geologic formations, and debris avalanches in streams caused by occasional episodes of high-intensity precipitation. Almost all

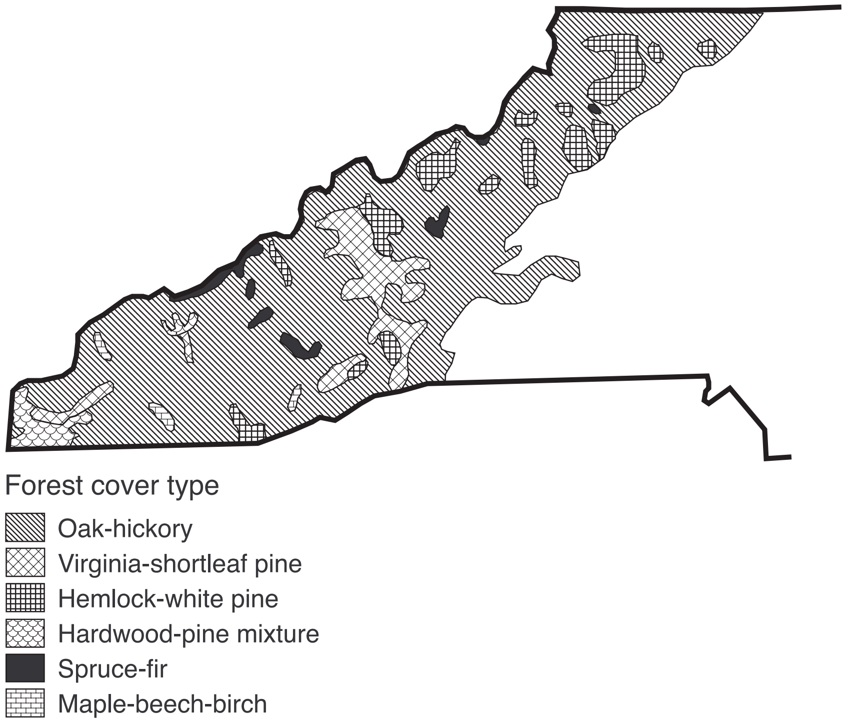


Figure 7—Generalized current forest cover types of the study area (North Carolina Forest Service 1955).

forests within the study area were logged during the late 1800s and early 1900s, and only small areas of old-growth forests remain, primarily on inaccessible, steep areas. Among the most devastating disturbances to forests of this region was introduction of the chestnut blight (*Cryphonectria parasitica*) during the early 1900s, which caused almost complete mortality of American chestnut, a species that dominated mountain slopes in the mid-elevation zone. Other serious exotic diseases and insects include dogwood anthracnose (*Discula destructiva*) and balsam woolly adelgid (*Adelges piceae*).

Field Data

Much of the vegetation data originated from the North Carolina Vegetation Survey (Peet and others 1998). Field data were obtained also from 20 investigations of vascular vegetation that had been conducted in the Southern Appalachian Mountains between 1976 and 1999 (table 1). Vegetation had been sampled throughout the entire study area, although sampling was clustered in about 10 locations. Several conspicuous areas in the region not sampled intensively include the low-elevation intermountain basins (highly disturbed by anthropogenic activities); the extreme southwest portion near Murphy (a low-elevation area of somewhat droughty soils derived from shaly, metasedimentary rocks); and moderate-to-high elevation sites on mountains along the North Carolina and Tennessee boundary. In the southern part of the study area, on the Nantahala National Forest, additional plots were installed where American ginseng was known to occur. Data from various studies were standardized by taxonomic nomenclature to account for variation in season of field sampling and apparent errors in species identification. Botanical nomenclature is derived from Weakley[5] where updates of the taxa have been completed, or from Kartesz (1999) for all remaining cases.

Natural stands generally > 75 years of age and not obviously recently disturbed were subjectively and randomly selected to represent uniform site conditions, e.g., similar aspect, landform, and species composition. Sampling methodologies of recent studies (after 1990) followed the North Carolina Vegetation Survey (Peet and others 1998); earlier studies used field methods of either Whittaker (1956) or Braun-Blanquet (1932). Field plot size was usually 0.1 ha (20 m by 50 m). In most plots ground area covered by each species was estimated first in 10-m by 10-m subplots using a

[5] Weakley, A.S. 2000. Flora of the Carolinas and Virginia. Unpublished draft. 500+ p. On file with: The University of North Carolina Herbarium, CB3280, Coker Hall, University of North Carolina, Chapel Hill, NC 27599.

Table 1—Characteristics of the Southern Appalachian vegetation dataset

Identification number	General location[a]	Plots	Species	Taxonomic resolution	Plot location confidence
		- - - - *number* - - - -			
05	Grandfather-Roan Mountains	74	495	High	High
07	Thompson River watershed	150	312	Moderate	Moderate
08	High-elevation red oak	61	227	Moderate	Moderate
09	Black and Craggy Mountains	156	370	Moderate	Moderate
10	Linville Gorge Wilderness area	181	403	High	Moderate
11	Shining Rock Wilderness area	160	433	High	Moderate
12	Kilmer-Slickrock Wilderness area	185	425	High	Moderate
13	Ellicott Rock Wilderness area	57	387	High	Moderate
18	Cedar hardwood woodlands	20	322	High	Moderate to high
20	Nantahala Mountains	91	724	High	High
21	Kelsey tract	18	146	High	Moderate
23	Chattooga Basin (intensive plots)	20	475[b]	Moderate	High
23	Chattooga Basin (survey plots)	532	475[b]	Moderate	High
37	Steels Creek watershed	48	178	Moderate	High
38	Craggy Mountains	29	260	Moderate	High
39	Great Smoky Mountains-uplands	172	450	Moderate	Moderate
40	Great Smoky Mountains-Tennessee and North Carolina	190	475	High	High
22	Highlands, NC, area	92	875	High	High
35	Chimney Rock and Hot Springs, NC	74	784	High	High

[a] Data from two studies (Wine Spring Creek in Macon County and a study of ginseng occurrence) were included in some models.
[b] Total number of species for both types of plots.

standard 10-class system, ranging from a trace to nearly 100 percent, then combined to determine mean plot cover. Ulrey (see footnote 3) provided additional information on the individual vegetative datasets.

Nonvegetative field data included only location of the field plot. Plot locations had been determined in the field using 7.5-minute scale topographic maps or geographic positioning system, which resulted in confidences of plot location of moderate or high, respectively. Although topographic data, e.g., elevation, aspect, and gradient, had been collected at each plot, these variables were determined from digital elevation models (DEMs) at the plot location because the derived models would be applied by GIS (Fels 1994). Soil nutrient data had been collected from a number of plots, but it could not be used in the analysis because lack of soil maps over much of the study area precluded application of prediction models. Sample plots were omitted from the analysis if careful examination of the data suggested they were outliers, which could have resulted, for example, from an erroneous plot location obtained from a topographic map.

Classification of Plant Communities for Ecological Zones

Eleven hypothesized ecological zones (table 2) were synthesized from 19 Southern Appalachian upland forest communities identified by Ulrey (see footnote 3) (appendix A). An overview of the classification methods and results are presented in appendix B. Using the classification scheme, individual plots within the Southern Appalachian vegetation dataset and the two supplementary datasets were objectively placed into a modified classification scheme of ecological zones based upon the experience and knowledge of the authors. The classification hierarchy is relatively coarse to aide in recognizing units in the field. The field plots were classified into groups of similar species composition using a sequence of constancy and ordered tables, indicator species analysis, followed by quantitative multivariate methods that included cluster analysis and indirect ordination. The goal of the classification was to identify units of compositionally similar vegetation for the purpose of inventory and assessment.

Table 2—Linkages among vegetation-based classification units of the upland forests' major group (appendix A) and hypothesized ecological zones that define areas of similar environments

Ecological group	Ecological subgroup[a]	Ecological zone
Spruce and fir forest	Fir forest	Spruce-Fir
	Spruce forest	Spruce-Fir
	Successional vegetation forest	Spruce-Fir
Northern hardwood forest	Yellow birch-spruce forest	Spruce-Fir
Northern hardwood forest	Beech gap and slope forest	Northern Hardwood
	Northern hardwood forest	Northern Hardwood
	Boulder field forest	Northern Hardwood
Northern hardwood forest	High-elevation red oak forest	High-Elevation Red Oak
Acid mesic forest	Acidic cove forest	Acidic Cove[b]
	Hemlock forest	Acidic Cove
Rich mesic forest	Rich cove forest	Rich Cove
Dry-mesic forest	Mesic montane oak-hickory forest	Mesic Oak-Hickory
Dry-mesic forest	Oak-hickory forest	Dry and Dry-Mesic Oak-Hickory
Xeric forest	Chestnut oak forest	Chestnut Oak Heath
Xeric forest	Shortleaf pine-oak forest	Shortleaf Pine-Oak Heath
Xeric forest	Table Mountain pine-pitch pine forest	Xeric Pine-Oak Heath and Oak Heath
Xeric forest	Subxeric oak-pine forest	White Pine-Oak Heath[c]

[a] Excluded are two minor, uncommon subgroups—calcareous dry-mesic forests and Carolina hemlock forests.
[b] Excluded are calcareous dry-mesic forests.
[c] Excluded are Carolina hemlock forests.

Classification of Geologic Formations for Fertility

Based largely on expert knowledge, a classification of geologic formations for fertility was developed that included eight primary lithologic groups (table 3). Group membership was based on rock characteristics that would produce soils of likely differing nutrient availability and water-holding capacity.[6] Rock characteristics considered in the classification included chemical composition, amount of potentially exchangeable base minerals, and texture. These formations were classified into fertility groups based on the major group and compositions of the primary and secondary rocks (appendix C). Lithologic group 1, for example, consisted of 47 major rock groups but only 35 unique geologic map units. The primary source for rock formation locations and descriptions was the geologic map of North Carolina (North Carolina Geological Survey 1985). Other sources included occasional 1:24,000 and 1:100,000 geologic maps; which were available for the Chattooga River watershed in northeast Georgia. Most rock groups occur as relatively large geographical areas, except for lithologic group 8, which tends to occur as small localized mineral bodies[7] ranging in area from 0.01 ha to about 1000 ha (0.03 acre to about 2,500 acres) (Stucky and Conrad 1958).

This classification is a first approximation and is based on recent classifications of bedrock formations for environmental

[6] Collins, T.K. Geo-fertility groups in the Southern Appalachians. Unpublished document. 2 p. with attachment. On file with: George Washington and Jefferson National Forests, 5162 Valleypointe Parkway, Roanoke, VA 24019–3050.

[7] No field plots were located in lithologic group 8, which occurs rarely in the study area.

Table 3—Classification of Southern Appalachian geologic formations that relate to soil fertility

Lithologic group	Map units[a]	Base status	Predominant bedrock composition
1[b]	47	High	Mafic formations, e.g. amphibolites
2[b]	5	High	Carbonate formations, e.g. limestones
3	19	Low	Formations with local zones of high mafic or high carbonate
4	43	Low	Granitics formations
5	27	Low	Sedimentary and metamorphic formations
6	47	Low	Quartzose with low fines formations
7	14	Low	Sulphidic formations
8	14	High	Ultramafic formations

[a] Listed in appendix C.
[b] Lithologic groups 1 and 2 were combined for analysis because their fertility properties were similar and few map units were available in group 2, most of which were associated with the Brevard geologic fault (appendix C).

or ecological analyses (Bricker and Rice 1989, McCartan and others 1998, Robinson and others 1999[8 9 10]). It also recognizes the relationships between vegetation and physical characteristics of rock formations found important in previous studies in the Southern Appalachians, such as Graves and Monk (1985), Mansberg and Wentworth (1984), McLeod (1988), Pittillo and others (1998), and Rohrer (1983). Strahler (1978) used similar logic to stratify rock types of the Appalachian Piedmont in Maryland into six lithologic groups for purposes of studying the distribution of vegetation. In a study of vegetation on rock outcrops in the Southern Appalachians, Wiser and others (1996) grouped 13 bedrock types into 3 generalized classes of minerals: mafic, felsic, or intermediate.

Vegetation and Environment Relationships

Critical to our study was an appropriate method of model development for ecological classification—a subject that has long received considerable attention (Austin 1987, Cairns 2001, Guisan and others 1999, Mora and Iverson 2002). Multiple discriminant analysis seems to be an obvious choice for classification because we had used it, apparently successfully, in previous studies [McNab and others 1999, Odom and McNab 2000 (see footnote 2)]. We did not use discriminant analysis in this study, however, primarily because we doubted that the underlying assumptions of normality of independent variables were satisfied (Press and Wilson 1978). The question of normality was particularly relevant in this analysis, which included eight binary response variables associated with geologic formations. Other reasons for not using discriminant analysis included lack of ability to: (1) apply weights to spatially constrain the models when applied at landscape scales (Mora and Iverson 2002), (2) select a subset of significant explanatory variables to achieve parsimonious models (Guisan and others 1999), and (3) modify predictions of the models in certain parts of the study area where we had specific knowledge of vegetation-environmental relationships (Cairns 2001). Other methods of multivariate analysis are available for classification purposes, such as principal components regression (Host and others 1996) and logistic regression (Wiser and others 1998).

We selected logistic regression for developing models to predict the probability of occurrence of plant communities in differing environments. Logistic regression can use both categorical and continuous variables and has less stringent assumptions of normality of independent variables

[8] Peper, J.D.; Grosz, A.E.; Kress, T.H. [and others]. 1995. Acid deposition sensitivity map of the Southern Appalachian assessment area, Virginia, North Carolina, Tennessee, South Carolina, Georgia, and Alabama. U.S. Geological Survey On-Line Digital Data Ser. Open-File Rep. 95–810. On file with: U.S. Department of the Interior, U.S. Geological Survey, 903 National Center, Reston, VA 20192. 1: 1,000,000 scale.

[9] Peper, J.D.; McCartan, Lucy B.; Horton, J. Wright, Jr.; Reddy, James E. 2001. Preliminary lithogeochemical map showing near-surface rock types in the Chesapeake Bay watershed, Virginia and Maryland. U.S. Geological Survey Open-File Rep. 01–187. On file with: U.S. Department of the Interior, U.S. Geological Survey, 903 National Center, Reston, VA 20192. 1: 500,000 scale.

[10] Robinson, G.R., Jr. 1997. Portraying chemical properties of bedrock for water quality and ecosystem analysis: an approach for New England. U.S. Geological Survey Open-File Rep. 97–154. On file with: U.S. Department of the Interior, U.S. Geological Survey, 903 National Center, Reston, VA 20192. 11 p.

(Hosmer and Lemeshow 2000, Press and Wilson 1978). It is commonly used to examine the importance of multiple independent variables on a binary outcome (Hosmer and Lemeshow 2000) but also has been used for purposes of discrimination and classification (Press and Wilson 1978). Logistic regression occasionally has been used to predict the probability of occurrence of plant species in response to environmental variables (Austin 1987, Margules and Stein 1989, McNab and Loftis 2002, ter Braak and Looman 1986, Wiser and others 1998) and the use of various forest habitats by wildlife (Odom and others 2001, van Manen and Pelton 1997). We also considered polytomous logistic regression, which is useful in classifying three or more possible outcomes, e.g., vegetation communities, but dismissed it because interpretation of results is difficult with more than two groups (Hosmer and Lemeshow 2000).

We used ordinary multiple logistic regression to determine environmental variables associated with the presence or absence of the 11 communities at field sample plot locations. Both presence and absence data characterized environmental limits of occurrence. For example, if 85 of the approximately 2,500 plots were classified as spruce-fir composition in the vegetation analysis it was assumed that environmental conditions (including other unmeasured factors, such as previous disturbance) at those locations were suitable to support spruce-fir plant communities, but were unsuitable at 2,415 locations where these conditions (and therefore these communities) were absent. We used a stepwise analysis procedure to develop the most parsimonious estimated logit of the multiple logistic regression model given by the generalized equation:

$$g(Y) = \beta_0 + \beta_1 X_1 + \ldots + \beta_i X_i + \beta_j D_1 + \ldots + \beta_j D_8 + \varepsilon$$

where

Y = the binary coded (0, 1) dependent variable for each of the 11 communities

β_0 = the intercept

$\beta_{1 \ldots j}$ = the coefficient of each independent variable

$X_{1 \ldots j}$ = the value of each continuous independent variable (appendix D)

$D_{1\text{–}8}$ = the binary value of each discrete independent variable (eight lithologic groups)

ε = residual error

Our procedure was a modification of the forward selection method, where variables are added to models that meet a minimum level of statistical significance. Instead of continuing to stay in the model, however, with the addition of each new significant variable, each previously included variable is tested for threshold significance level and retention. We used a minimum significance level of $P < 0.05$ for retaining independent variables. The goal of our analysis was correct classification of sample plots into two categories: present or absent. We used BioMedical Data Processing statistical software for statistical analysis.[11] Using methodology similar to Wiser and others (1998), we developed a "stand alone" model for each of the 11 communities, which approximated ecological zones because it established a relationship between vegetation and its associated environment.

Model accuracy was evaluated using several standard measures of logistic regression performance, which included classification tables, receiver operating characteristic (ROC) curves, and selection of probability cutpoints using sensitivity and specificity. Two-way classification tables allowed evaluation of the performance of each model by comparison of observed and classified observations at specific probability cutpoints. A cutpoint is the level of estimated probability selected for the binary classification of an observation that represents occurrence or nonoccurrence of a plant community. Incorrect classifications are displayed in the two-way table as false occurrence or false nonoccurrence. The initial classification cutpoint for each model was set at the greatest value of combined sensitivity and specificity. Sensitivity is a measure of accuracy for predicting an occurrence and specificity is a measure for predicting nonoccurrence. Because the rates of change in sensitivity and specificity may differ in some models, ROC curves provide a graphic means of assessing the accuracy of a logistic model. A ROC curve is a plot of sensitivity over 1 minus specificity with values that range from zero to 1. A model with an area under the ROC curve > 0.7 is considered to have acceptable discrimination capability; models with ROC values > 0.8 are considered to be excellent (Hosmer and Lemeshow 2000). Our classification models are likely biased because an independent dataset was not used for evaluation. Jackknifing was considered as a means of unbiased model testing, but was rejected because our study was largely exploratory. Regression coefficients are omitted because the ecological zone models have not been tested and are considered preliminary.

Database Creation and Model Application

Application of the environmental variable-based ecological zone models required development of a spatial database for the study area. Source data were acquired from U.S.

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[11] BioMedical Data Processing. Los Angeles, CA. Release 7. Software initially developed by University of Southern California, but with limited commercially availability as of 2004.

Geological Survey 30-m resolution DEMs. Edge matching and smoothing procedures were applied to all DEMs using the ArcGrid[12] GIS to produce a seamless grid of elevations for the entire study area. This elevation grid was processed using algorithms to produce estimates of derived terrain and environmental variables; e.g., aspect, slope gradient, slope length.

All vegetation plots were located using a global positioning system (GPS) or from 1:24,000-scale topographic map latitude and longitude coordinates. A GIS was used to assign each vegetative plot to the appropriate cell in the DEM. Environmental variables were determined for each plot by merging the location with the 30-m resolution digital elevation grids. In total, 25 grids were merged with each of the 25 thematic GIS layers. A database was created that included the plot number, vegetation classification type, and four groups of environmental characterization variables: landscape, landform, site, and geographic. The two landscape variables included dormant-season and growing-season rainfall. Eleven landform variables included: (1) landform index, (2) weighted landform index, (3) landform shape 8, (4) landform shape16, (5) landform index surface interaction, (6) weighted landform index surface interaction, (7) length of slope, (8) slope position, (9) distance to bottom, (10) distance to intermittent stream, and (11) slope direction. Site variables included elevation, terrain shape index, surface curvature profile, surface curvature planiform, curvature, slope steepness, slope steepness and slope position interaction, and geologic fertility group. Four geographic variables included x coordinates, y coordinates, distance from Murphy, NC, and distance from the Blue Ridge Escarpment. The geographic variables were included in the analysis to account for other environmental variation not accounted for, such as temperature and evapotranspiration and the effect of past climates on current plant community distribution. A brief description of these components is presented in appendix D.

Each of the 11 logistic ecological zone models was applied to the DEMs representing environmental, geologic, and landform variables. The resulting 11 map layers represent the probability of occurrence, ranging from zero to 1, of each ecological zone in each 30-m (98-foot) cell of the DEM grid for the 5.6-million-acre study area. The initial cutpoint of each model allowed the matrix of probabilities predicted to be classified in two groups: presence of the ecological zone or absence of the ecological zone. Clusters of cells where the ecological zone was classified as present represent bands of probabilities, from the cutpoint (where we are fairly sure the ecological zone occurs) to near 1.0 (where we are almost absolutely confident the ecological zone occurs). Typically, the centers of areas of highest probabilities were at sample plot locations, where environmental data were obtained to generate the ecological zone model. This spatial representation of ecological zones made it possible to evaluate their distribution based on model sensitivity and specificity. This process is similar to procedures used in wildlife habitat modeling using GIS (Clark and van Manen 1993, Star and Estes 1990, van Manen and Pelton 1997).

Mapping of ecological zones involved combining individual models to form a single GIS coverage and establishing a boundary in the transition area between adjacent ecological zones. The boundaries often are broad and usually support more than one community. Factors contributing to model errors, e.g., predicted co-occurrence of two or more ecological zones for the same site, were accuracy of the vegetation classification, sample size for model development, appropriate independent variables, robustness of the mathematical modeling algorithms, initial cutpoints of the classification matrix, whether values of the represented environmental variables occurred within the range sampled or required extrapolation, and other factors. Individual ecological zone models were developed independently of other models and varied in their predictive capability.

We used the stacking order feature in ArcGrid to resolve classification conflicts in areas where multiple ecological zones were predicted. All ecological zones were arranged in vertical sequence from highest, on top of the stack, to lowest predictive power. Themes in ArcGrid at the top of the stack take precedence over those below, so in areas of overlap, the upper themes in descending order obstruct the view of those below. Using an iterative process, stacking order and probability cutpoints were adjusted until the pattern of ecological zones appeared reasonable. During this process approximately 10 ecological zone maps representing various parts of the study area were continuously viewed to evaluate the effect of stacking order, probability of occurrence, and reasonableness of ecological zone distribution. These areas represented the range of environmental conditions from lower to upper elevations, from escarpment to mountains, and from north to south of the Asheville Basin. Digital orthophotoquads were used to evaluate some of the more complex areas. A summary of the process used to develop the regional ecological zone map is shown in figure 8.

[12] ArcGrid is a trademark and commercial product of Environmental Systems Research Institute Corporation and consists of a collection of cell-based spatial analysis tools.

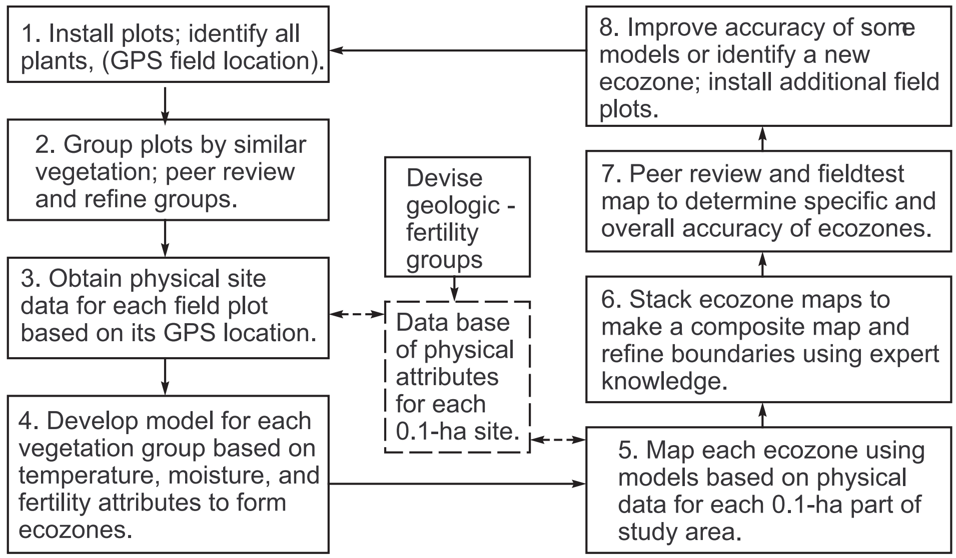

Figure 8—Outline of the methods used to develop the ecological zone map (GPS = global positioning system).

Results

We identified 11 ecological zones in the Southern Appalachians of North Carolina (table 2). Two ecological zones, however, Spruce-Fir and Northern Hardwood, were subdivided into northern and southern districts for development of satisfactory models, which results in a total of 13 models. To reduce possible confusion, however, we will refer to the models collectively numbering 11, 1 for each ecological zone. The centrally located, generally east-west oriented Asheville Basin provided an arbitrary, but logical place to subdivide the study area into north and south districts for the Spruce-Fir and Northern Hardwoods ecological zones.

Statistics associated with development of the models are presented in tables 4 and 5. Model performance indicated by classification accuracy at various logistic regression cutpoints is presented in tables 6 and 7. An example of the method used to select the optimum cutpoint is presented for the Spruce-Fir (south) model (table 8). The ROC used to evaluate the Spruce-Fir model is shown in figure 9. The area under the curve equals 0.95, which suggests the model has outstanding discrimination capability (Hosmer and Lemeshow 2000). The high ROC values of most logistic models suggest that plant communities described by Ulrey (see footnote 3), some of which were combined for this study, are associated with sites having unique environmental characteristics.

For convenience and ease of recognition, ecological zones are named for their dominant plant community. The names are widely recognized in the literature, although ecological

Table 4—Number of plots, classification accuracy, and fit statistics of logistic regression models for ecological zones in high-elevation environments

	Spruce-Fir		Northern Hardwood		
Item	South	North	South	North	High-elevation red oak
Plots present (no.)	59	26	71	33	137
Plots absent (no.)	384	118	884	287	1,138
Cutpoint (proportion)	0.46	0.63	0.14	0.19	0.22
Overall accuracy (percent)	93	92	84	81	85
Receiver operator characteristics (proportion)	0.95	0.95	0.84	0.85	0.81

Table 5—Number of plots, classification accuracy, and fit statistics of logistic regression models for ecological zones in low-elevation environments

Item	Acidic Cove	Rich Cove	Mesic Oak-Hickory	Chestnut Oak Heath	Dry and Dry-Mesic Oak-Hickory	White Pine-Oak Heath	Xeric Pine-Oak Heath and Oak Heath	Shortleaf Pine-Oak Heath
Plots present (no.)	262	601	237	192	308	106	151	121
Plots absent (no.)	2,371	1,874	2,145	2,283	2,167	2,369	2,324	2,354
Cutpoint (proportion)	0.21	0.58	0.11	0.14	0.41	0.10	0.11	0.53
Overall accuracy (percent)	82	80	69	77	85	84	80	95
Receiver operator characteristics (proportion)	0.80	0.83	0.65	0.77	0.88	0.84	0.79	0.95

Table 6—Cutpoints and classification results (percent of plots predicted correctly as present or absent) of logistic regression models for ecological zones in high-elevation environments

Cut-point	Spruce-Fir				Northern Hardwood				High-elevation red oak	
	South		North		South		North			
	P	A	P	A	P	A	P	A	P	A
	percent									
0.1	92	85	92	78	66	83	91	73	75	72
0.2	86	91	85	87	27	95	42	85	52	89
0.3	80	94	77	90	13	97	39	94	29	95
0.4	70	96	69	97	6	99	0	97	13	98
0.5	61	97	65	98	0	99	0	99	8	99
0.6	41	97	65	98	0	99	0	100	2	100
0.7	34	98	57	100	0	100	0	100	0	100
0.8	25	100	42	100	0	100	0	100	0	100
0.9	17	100	34	100	0	100	0	100	0	100

P = present; A = absent.

Table 7—Cutpoints and classification results (percent of plots predicted correctly as present or absent) of logistic regression models for ecological zones in low-elevation environments

Cut-point	Acidic Cove		Rich Cove		Mesic Oak-Hickory		Chestnut Oak Heath		Dry-Mesic Oak-Hickory		White Pine-Oak Heath		Xeric Pine-Oak Heath		Shortleaf Pine-Oak Heath	
	P	A	P	A	P	A	P	A	P	A	P	A	P	A	P	A
	percent															
0.1	72	73	92	47	52	70	58	82	91	75	44	91	50	87	81	93
0.2	50	88	78	71	3	97	27	95	78	83	15	98	21	96	68	96
0.3	28	95	68	84	0	100	11	98	58	89	6	100	9	99	61	98
0.4	11	98	52	91	0	100	4	99	25	95	3	100	4	100	53	99
0.5	3	100	38	94	0	100	1	100	14	98	1	100	1	100	47	99
0.6	0	100	27	97	0	100	0	100	4	99	0	100	0	100	39	99
0.7	0	100	17	98	0	100	0	100	1	100	0	100	0	100	23	100
0.8	0	100	9	99	0	100	0	100	0	100	0	100	0	100	13	100
0.9	0	100	5	100	0	100	0	100	0	100	0	100	0	100	3	100

P = present; A = absent.

Table 8—Accuracy of classification for the logistic model describing the Spruce-Fir Zone (south) based on varying cutpoints

	Plots				Percentages				
	Correct		Incorrect						
Cut-point	Event	Nonevent	Event	Nonevent	Overall correct	Sensi-tivity	Speci-ficity	False positive	False negative
0.113	54	327	5	57	86.0	91.5	85.2	14.8	8.5
0.213	51	351	8	33	90.7	86.4	91.4	8.6	13.6
0.313	47	361	12	23	92.1	79.7	94.0	6.0	20.3
0.413	41	368	18	16	92.3	69.6	95.8	4.2	30.5
0.463[a]	41	371	18	13	93.0	69.5	96.6	3.4	30.5
0.512	36	372	23	12	92.1	61.0	96.9	3.1	39.0
0.613	24	372	35	12	89.4	40.7	96.9	3.1	59.3
0.713	20	377	39	7	89.6	33.9	98.2	1.8	66.1
0.813	15	382	44	2	89.6	25.4	99.5	0.5	74.6
0.913	10	383	49	1	88.7	16.9	99.7	0.3	83.1

[a] Selected as optimum cutpoint.

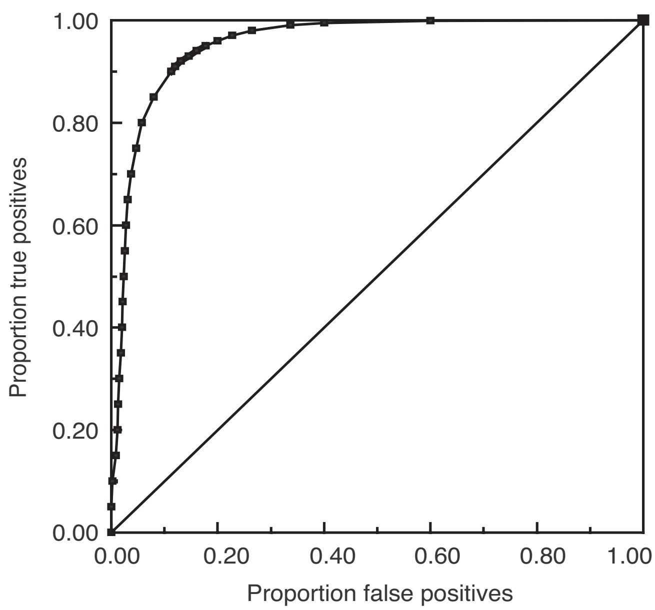

Figure 9—Receiver operating characteristic (ROC) curve for the Spruce-Fir (south) logistic model. The proportion of area under the ROC curve is 0.9501.

zones could have been named for the prevailing environmental conditions they represent, such as cold, submesic, and mesotrophic for Spruce-Fir. Models for the Spruce-Fir, Northern Hardwood, and Acidic Cove Zones included more than one ecological subgroup, which made it difficult to separate plant communities using the coarse scale of variables in our analysis and highlighted the importance of microhabitat influences in these types. The 11 ecological zones with unique climatic, topographic, and geologic features and important indicator species are presented in the following section, grouped by high- and low-elevation environments.

High-Elevation Environments

Spruce-Fir—This zone includes spruce, fir, and yellow birch-spruce forests and high-elevation successional tree, shrub, and sedge communities. Eighty-five field plots were used to characterize the Spruce-Fir Zone, and they contained 185 species—22 trees, 34 shrubs, 126 herbs, and 3 vines. Indicator species and species with high constancy or abundance included: Fraser fir, red spruce, American mountain-ash, yellow birch, mountain woodfern, Pennsylvania sedge, mountain woodsorrel, hobblebush, fire cherry, and Catawba rhododendron.

The relationship between the Spruce-Fir Zone and the physical environment was determined with two models. South of the Asheville Basin, overall model accuracy is 93 percent—68 percent for areas predicted to have the Spruce-Fir Zone present and 96 percent for areas predicted to have it absent. In this area, the zone is primarily at high elevations, away from low-base sedimentary and metamorphic rock; secondarily, it occurs near streamheads in areas with high growing-season rainfall. Predictive model variables are presented in table 9.

North of the Asheville Basin, overall model accuracy is 92 percent—65 percent in areas predicted to have the Spruce-Fir Zone present and 97 percent in areas predicted to have it absent. In this area, the zone is primarily at high elevations to the northeast; secondarily, it occurs well above the heads of streams on broad ridges within low-base metamorphic

Table 9—Environmental variables included in ecological zone models for three high-elevation environments—two zones, Spruce-Fir and Northern Hardwood, were modeled as occurring either south or north of the Asheville Basin

Environmental variable	Spruce-Fir South	Spruce-Fir North	Northern Hardwood South	Northern Hardwood North	High-elevation red oak
Dormant-season rainfall	8–	—	—	5–	—
Growing-season rainfall	4+	—	6+	—	6+
Landform index	—	—	—	—	—
Weighted landform index	10+	—	3+	—	1–
Landform shape8	—	9+	—	—	—
Landform shape16	—	5–	—	—	9+
Landform index times surface	—	—	—	—	—
Weighted landform index times surface	5+	—	—	—	—
Length of slope	6+	—	—	—	—
Slope position	—	—	5–	—	—
Distance to bottom	3–	—	—	—	—
Distance to intermittent stream	9+	3–	—	—	—
Slope direction-aspect	—	8+	—	—	—
Elevation	1+	1+	1+	3+	3+
Terrain shape index	7–	—	—	—	—
Surface curvature profile	—	—	—	—	—
Surface curvature planiform	—	—	—	—	—
Curvature	—	—	—	—	5–
Slope steepness	—	—	—	—	4+
Slope times slope position	—	6–	—	—	—
Geo1and 2: high-base status formations	—	—	—	1+	—
Geo3: low-base status with high inclusions	—	7–	—	4+	—
Geo4: low-base granitics formations	—	—	—	—	8–
Geo5: low-base sedimentary and metamorphic formations	2–	—	—	—	2+
Geo6: low-base quartzitic formations	—	—	—	—	—
Geo7: low-base sulphidic formations	—	—	—	—	7+
Geo8: ultramafic formations	—	—	—	—	—
x coordinates	—	2+	2–	—	—
y coordinates	—	4–	—	—	—
Distance from Murphy, NC	—	—	4+	2+	—
Distance from Blue Ridge Escarpment	—	—	—	—	—

— = Variable not significant in the final regression model.
Numbers in columns indicate the relative level of importance of significant variables in each ecozone model and sign of the coefficient.

rock having inclusions of high-base rock. Seven environmental and two spatial variables are significant (table 9).

Northern Hardwood—This zone includes beech gaps and slopes, boulder fields, and northern hardwood forests. One hundred and four field plots were used to characterize it and they contained 308 species—36 trees, 35 shrubs, 232 herbs, and 5 vines. Indicator species and species with high constancy or abundance included: mountain holly, Allegheny serviceberry, Pennsylvania sedge, yellow birch, American beech, sugar maple, northern red oak, Roan snakeroot, Canadian woodnettle, and wild leeks or ramps.

Two models were needed to express the relationship of the Northern Hardwood Zone with environmental factors. South of the Asheville Basin, overall model accuracy is

84 percent—51 percent in areas predicted to have the zone present and 87 percent in areas predicted to have the zone absent. In this area, the Northern Hardwood Zone is primarily at higher elevations on somewhat protected landscapes in the northwestern portion of western North Carolina; secondarily, it occurs on upper slopes in areas of higher growing-season rainfall. The logistic model includes six significant variables (table 9).

North of the Asheville Basin, the overall accuracy of the model is 81 percent—42 percent in areas predicted to have the zone present and 85 percent in areas predicted not to have it. In this area, the Northern Hardwood Zone is primarily on high-base rock at higher elevations well northeast of the southwest corner of North Carolina; secondarily, it occurs where there are inclusions of high-base rock within a matrix of low-base rock in areas with lower dormant-season rainfall. Five variables had a significant relationship in this model (table 9).

High-Elevation Red Oak—This zone includes forests dominated by northern red oak. One hundred and thirty-seven plots were used to characterize it and they contained 335 species—46 trees, 45 shrubs, 236 herbs, and 8 vines. Indicator species and species with high constancy or abundance included: American chestnut, flame azalea, whorled yellow loosestrife, northern red oak, Pennsylvania sedge, speckled wood-lily, highbush blueberry, mountain laurel, and New York fern.

The overall accuracy of the model is 85 percent—52 percent in areas predicted to have the High-Elevation Red Oak Zone present and 89 percent in areas predicted not to have it. It is found primarily on exposed sites on low-base sedimentary and metamorphic rock at higher elevations; secondarily on steeper, convex slopes in areas with higher growing-season rainfall on low-base sulphidic and low-base granitic rock. Predictive model variables are presented in table 9.

Low-Elevation Environments

Acidic Cove—This zone includes hemlock and mixed mesophytic forests typically dominated by an evergreen understory. Two hundred and sixty-two plots were used to characterize the Acidic Cove Zone and they contained 387 species—61 trees, 45 shrubs, 265 herbs, and 16 vines. Indicator species and species with high constancy or abundance included: partridgeberry, great laurel, Canada hemlock, black birch, heartleaf species, mountain doghobble, eastern white pine, yellow-poplar, common greenbrier, and red maple.

Overall, accuracy of the model is 82 percent—57 percent in areas predicted to have the zone present and 85 percent in areas predicted not to have it. The Acidic Cove Zone is primarily on lower slopes at lower elevations, areas with high growing-season rainfall and low dormant-season rainfall, and concave land surface shape. Secondarily, it occurs near perennial streams on low-base granitic rock or away from high-base rock. Eleven variables were significant (table 10).

Rich Cove—This zone includes mixed mesophytic forests typically dominated by a diverse herbaceous understory. Six hundred and one plots were used to characterize the Rich Cove Zone and they contained 636 species—75 trees, 68 shrubs, 471 herbs, and 22 vines. Indicator species and species with high constancy or abundance include: black cohosh, American ginseng, blue cohosh, mandarin, bloodroot, northern maidenhair fern, Dutchman's pipe, rattlesnake fern, mountain sweet-cicely, Appalachian basswood, yellow buckeye, white ash, yellow-poplar, and northern red oak.

Overall, the accuracy of the model is 80 percent—68 percent in areas where the zone is predicted to be present and 84 percent in areas where it is not. The Rich Cove Zone occurs primarily in protected landscapes away from the escarpment in areas with moderate growing-season rainfall on more gentle slopes; secondarily, it occurs at higher elevations, on long slope segments nearer the heads of streams, more southerly latitudes, and away from low-base quarzitic or sulphidic rock. There is a weak positive correlation to high-base rock. The predictive model included 13 variables (table 10).

Mesic Oak-Hickory—This zone includes mesic mixed-oak and oak-hickory forests. Two hundred and thirty-seven plots were used to characterize the Mesic Oak-Hickory Zone, and they contained 416 species—60 trees, 45 shrubs, 295 herbs, and 16 vines. Indicator species and species with high constancy or abundance include: white oak, flowering dogwood, northern red oak, Canada richweed, mockernut hickory, New York fern, pignut hickory, chestnut oak, speckled wood-lily, and rattlesnakeroot.

Overall, the accuracy of the model is 69 percent—52 percent in areas predicted to have the zone present and 91 percent in areas predicted not to have it. The Mesic Oak-Hickory Zone is found primarily at lower and midelevations in areas with higher dormant-season rainfall; secondarily, it occurs in areas with low-base rock having inclusions of high-base rock and away from broad, gentle sloping landscapes. Four variables were significant in the prediction model (table 10).

Chestnut Oak Heath—This zone includes xeric to dry mixed-oak forests typically dominated by an evergreen understory. One hundred and ninety-two plots were used to characterize the Chestnut Oak Heath Zone and they contained 297 species—56 trees, 45 shrubs, 187 herbs, and

Table 10—Environmental variables included in ecological zone models for three low-elevation environments—two zones, Spruce-Fir and Northern Hardwood, were modeled as occurring either south or north of the Asheville Basin

Environmental variable	Acidic Cove	Rich Cove	Mesic Oak-Hickory	Chestnut Oak Heath	Dry-Mesic Oak-Hickory	White Pine-Oak Heath	Xeric Pine-Oak Heath	Shortleaf Pine-Oak Heath
Dormant-season rainfall	4–	—	1+	11–	2+	—	5–	—
Growing-season rainfall	3+	3–	—	6+	—	3+	11+	9–
Landform index	—	—	—	—	—	—	—	—
Weighted landform index	—	1+	—	—	5–	7–	—	3–
Landform shape8	—	—	—	—	—	—	—	10+
Landform shape16	—	—	4–	—	—	—	10+	4–
Landform index times surface	7–	6–	—	—	—	11–	—	—
Weighted landform index times surface	—	10+	—	9–	—	9+	—	—
Length of slope	6–	7+	—	—	—	—	9–	—
Slope position	1+	—	—	13–	—	5–	—	8–
Distance to bottom	—	—	—	—	—	—	3+	—
Distance to intermittent stream	8+	11–	—	—	—	—	—	—
Slope direction-aspect	—	—	—	—	—	12–	—	—
Elevation	2–	5+	2–	8–	1–	1–	6–	1–
Terrain shape index	—	—	—	—	11–	—	—	5–
Surface curvature profile	5+	—	—	—	—	—	—	6–
Surface curvature planiform	11+	—	—	10+	—	—	—	—
Curvature	—	—	—	12–	9–	—	7+	—
Slope steepness	—	4–	—	—	12+	—	—	—
Slope times slope position	—	—	—	—	—	8+	—	—
Geo1and 2: high-base status formations	9–	13+	—	—	8+	—	—	—
Geo3: low-base status with high inclusions	—	—	3+	—	7+	—	—	—
Geo4: low-base granitics formations	10+	—	—	—	10+	10+	4+	11+
Geo5: low-base sedimentary and metamorphic formations	—	—	—	—	—	—	8+	—
Geo6: low-base quartzitic formations	—	9–	—	7+	—	—	1+	—
Geo7: low-base sulphidic formations	—	12–	—	1+	—	—	2+	—
Geo8: ultramafic formations	—	—	—	—	—	—	—	—
x coordinates	—	—	—	5+	3–	—	—	7–
y coordinates	—	8–	—	3+	6+	4+	—	2–
Distance from Murphy, NC	—	—	—	4–	—	6–	—	—
Distance from Blue Ridge Escarpment	—	2+	—	2–	4–	2–	—	—

— = Variable not significant in the final regression model.
Numbers in columns indicate the relative level of importance of significant variables in each ecozone model and sign of the coefficient.

9 vines. Indicator species and species with high constancy or abundance include: chestnut oak, northern red oak, great laurel, red maple, mountain laurel, Canada hemlock, galax, common greenbrier, and sourwood.

Overall, the accuracy of the model is 77 percent—62 percent in areas where it is predicted present and 79 percent in areas where the zone is predicted not to be. It is found primarily in the southwestern portion of the Southern Appalachians in North Carolina on low-base sulphidic rock in areas with higher growing-season rainfall; secondarily, it occurs on low-base quarzitic rock at lower elevations on convex, exposed, upper slopes in areas with lower dormant-season rainfall. The best predictive model included 13 significant variables (table 10).

Dry and Dry-Mesic Oak-Hickory—This zone includes dry and dry-mesic mixed oak and oak-hickory forests. Three hundred and eight plots were used to characterize this zone and they contained 420 species—60 trees, 50 shrubs, 294 herbs, and 16 vines. Indicator species and species with high constancy or abundance include: scarlet oak, sourwood, bear huckleberry, mountain laurel, giant cane, white oak, hillside blueberry, blackgum, flowering dogwood, and eastern white pine.

Overall, the accuracy of the model is 85 percent—58 percent in areas predicted to have the zone present and 89 percent in areas predicted not to have it. The Dry and Dry-Mesic Oak-Hickory Zone is found primarily at lower elevations, northwest but near the escarpment in areas with higher dormant-season rainfall; secondarily, it occurs on more exposed landscapes with a convex land surface and steeper slopes within low-base rock with high-base rock inclusions, high-base rock, and low-base granitic rock (table 10).

White Pine-Oak Heath—This zone includes dry mixed pine-oak forests typically dominated by eastern white pine. It may represent the transition between xeric pine and pine-oak, and dry-mesic oak plant communities. One hundred and six plots were used to characterize the zone and they contained 219 species—42 trees, 35 shrubs, 133 herbs, and 9 vines. Indicator species and species with high constancy or abundance include: eastern white pine, scarlet oak, sourwood, chestnut oak, bear huckleberry, mountain laurel, hillside blueberry, and blackgum.

Overall, the accuracy of the model is 84 percent—55 percent in areas predicted to have the zone present and 86 percent in areas predicted not to have it. The White Pine-Oak Heath Zone is found primarily at lower elevations near the central part of the escarpment in areas with higher growing-season rainfall; secondarily, it occurs in exposed upper slopes on low-base granitic rock with more southerly exposure. The predictive model includes 12 significant variables (table 10).

Xeric Pine-Oak Heath and Oak Heath—This zone includes xeric pine, pine-oak, and oak forests typically dominated by an evergreen understory. One hundred and fifty-one plots were used to characterize it and they contained 234 species—48 trees, 43 shrubs, 134 herbs, and 9 vines. Indicator species and species with high constancy or abundance include: Table Mountain pine, scarlet oak, pitch pine, black huckleberry, chestnut oak, wintergreen, trailing arbutus, mountain laurel, hillside blueberry, and maleberry.

Overall, the accuracy of the model is 80 percent—58 percent in areas predicted to have the zone present and 82 percent in areas predicted not to have it. The Xeric Pine-Oak Heath and Oak Heath Zone is found primarily on all low-base rocks in upper slopes in areas with low dormant-season rainfall; secondarily, it occurs at lower elevations on broad, gentle slopes and ridges with a flat-to-convex surface shape. The best model included 11 variables (table 10).

Shortleaf Pine-Oak Heath—This zone includes xeric pine and pine-oak forests dominated by shortleaf pine. One hundred and twenty-one plots were used to characterize it and they contained 262 species—46 trees, 42 shrubs, 163 herbs, and 11 vines. Indicator species and species with high constancy or abundance include: shortleaf pine, sourwood, sand hickory, scarlet oak, southern red oak, post oak, hillside blueberry, American holly, featherbells, and spring iris.

Overall, the accuracy of the model is 95 percent—65 percent in areas predicted to have the zone present and 97 percent in areas predicted not to have it. The Shortleaf Pine-Oak Heath Zone is found primarily at low elevations on broad, exposed landforms in the southwestern portion of the Southern Appalachians in North Carolina having convex surface shape; secondarily, it occurs on upper slopes in areas with low growing-season rainfall and low-base granitic rock. Eleven variables were included in the model (table 10).

Summary of Model Components

Elevation was the only variable present in all models and usually ranked first or second in importance. Next in importance were geologic group and precipitation, which were present in all but one of the models. A measure of landform type or slope shape was present in most models. Aspect was relatively unimportant in the models, likely because its effect was accounted for by weighted landform index. Topographic variables, particularly a measure of landform, were more important in the low-elevation models than in the high-elevation models.

Mapped Ecological Zones

Distribution of the 11 ecological zones in relation to hypothesized (see footnote 3) midpoints (not ranges) of their associated temperature, moisture, and fertility regimes are shown in figure 10. Not shown there are ranges of occurrence of each ecological zone relative to the environmental components. Application of these relationships in a site-by-site classification of the landscape would result in a map of ecological zones. However, direct application of this diagram in a site-by-site classification of a barren landscape would be difficult because compensating topographic factors almost always are present and make it difficult to assess moisture regimes. For example, a site on a lower south-facing slope may have soil moisture conditions equivalent to an upper, north-facing slope. Variation in precipitation would include additional complexity. Mathematical models quantify the complex, compensating relationships among variables.

Occurrences of ecological zones across the Southern Appalachian landscape were predicted based on the 11 mathematical models that used DEMs for the primary data source, as illustrated for Wayah Bald (fig. 11). Each of the 11 models was applied to the approximate 175,000 cells (or sites) in the

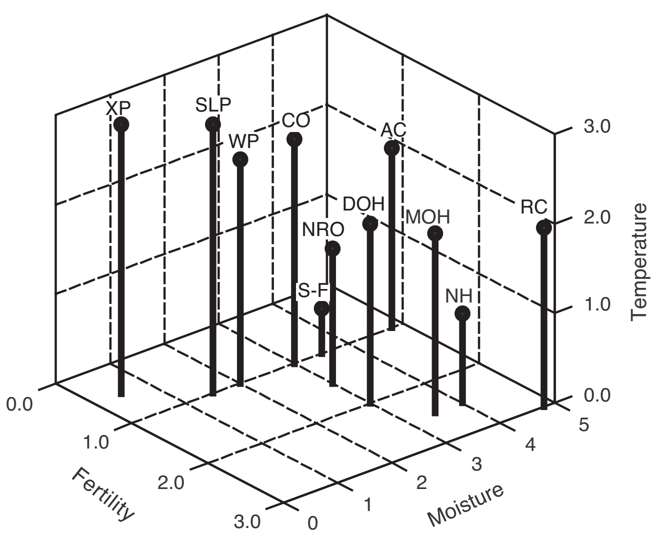

Figure 10—Hypothesized distribution of ecological zones in relation to temperature, moisture, and fertility gradients. Temperature regimes range from low (0.0) to average (1.5) to high (3.0), moisture ranges from low (0.0), to average (3.0) to high (5.0), fertility ranges from low (0.0) to average (1.5) to high (3.0). Abbreviations of ecological zones are: Acidic Cove (AC), Chestnut Oak-Heath (CO), Dry and Dry-Mesic Oak-Hickory (DOH), Mesic Oak-Hickory (MOH), Northern Hardwood (NH), High-Elevation Red Oak (NRO), Rich Cove (RC), Shortleaf Pine-Oak Heath (SLP), Spruce-Fir (S-F), White Pine-Oak Heath (WP), Xeric Pine-Oak Heath and Oak Heath (XP).

DEM, resulting in assignment of each site to the ecological zone of highest predicted probability. Consider, for example, the site at the peak of Wine Spring Bald, shown on the DEM with elevation of 1658 m (5,440 feet). If the probabilities predicted by application of the models on that site ranged from 0.001 (Dry Oak-Hickory) to 0.985 (High-Elevation Red Oak), then it is highly likely that environmental conditions there are most suitable for the latter ecological zone and the site was classified as such. Polygons of ecological zones were not subjectively delineated on the DEM, but are formed by varying-sized clusters of similarly classified sites, which represent a landscape map of recurring vegetative patterns. Ten ecological zones are predicted to occur on the landscape within the Wayah Bald DEM with High-Elevation Red Oak, Dry and Dry-Mesic Oak-Hickory, and Rich Cove being most abundant; Spruce-Fir is absent. The models were applied in a similar manner to 146 other DEMs of the study area.

The joined quadrangles provide a map of predicted ecological zones on approximately 5.6 million acres in the Southern Appalachians (fig. 12). Mesic Oak-Hickory and Acidic Cove are the most extensive ecological zones in this area; Spruce-Fir and Chestnut Oak Heath are the least extensive (table 11). Except for two types, ecological zones occur in roughly the same proportions on the Nantahala and Pisgah National Forests as on non-Forest Service land. These are Shortleaf Pine-Oak Heath, represented in a much greater proportion on non-Forest Service land and Xeric Pine-Oak Heath and Oak Heath, represented in a much greater proportion of the Nantahala and Pisgah National Forests. These differences reflect the location of National Forest System lands at high elevations in the Southern Appalachians.

Preliminary Validation of the Ecological Zone Map

In addition to using ArcGrid and aerial photos to validate the models, we also completed an initial field validation of the Rich Cove Zone, an uncommon but floristically distinctive type that commonly occurs on sites with above average soil fertility (McLeod 1988, Newell and others 1999, Schafale and Weakley 1990). The first test there was part of the logistic regression routine. In that test, model accuracy, based on plots from which the model was derived, was 80 percent overall for Rich Cove; 52 percent for areas predicted to have Rich Cove present (sensitivity) and 91 percent for areas predicted not to have Rich Cove (specificity) (table 7). In the summer of 2000, over 70 randomly selected plots on the Nantahala and Pisgah National Forests were visited to begin field validation and refinement of the Rich Cove Zone model. For these field plots, we found results similar to the first test—55 percent of the predicted Rich Cove plots

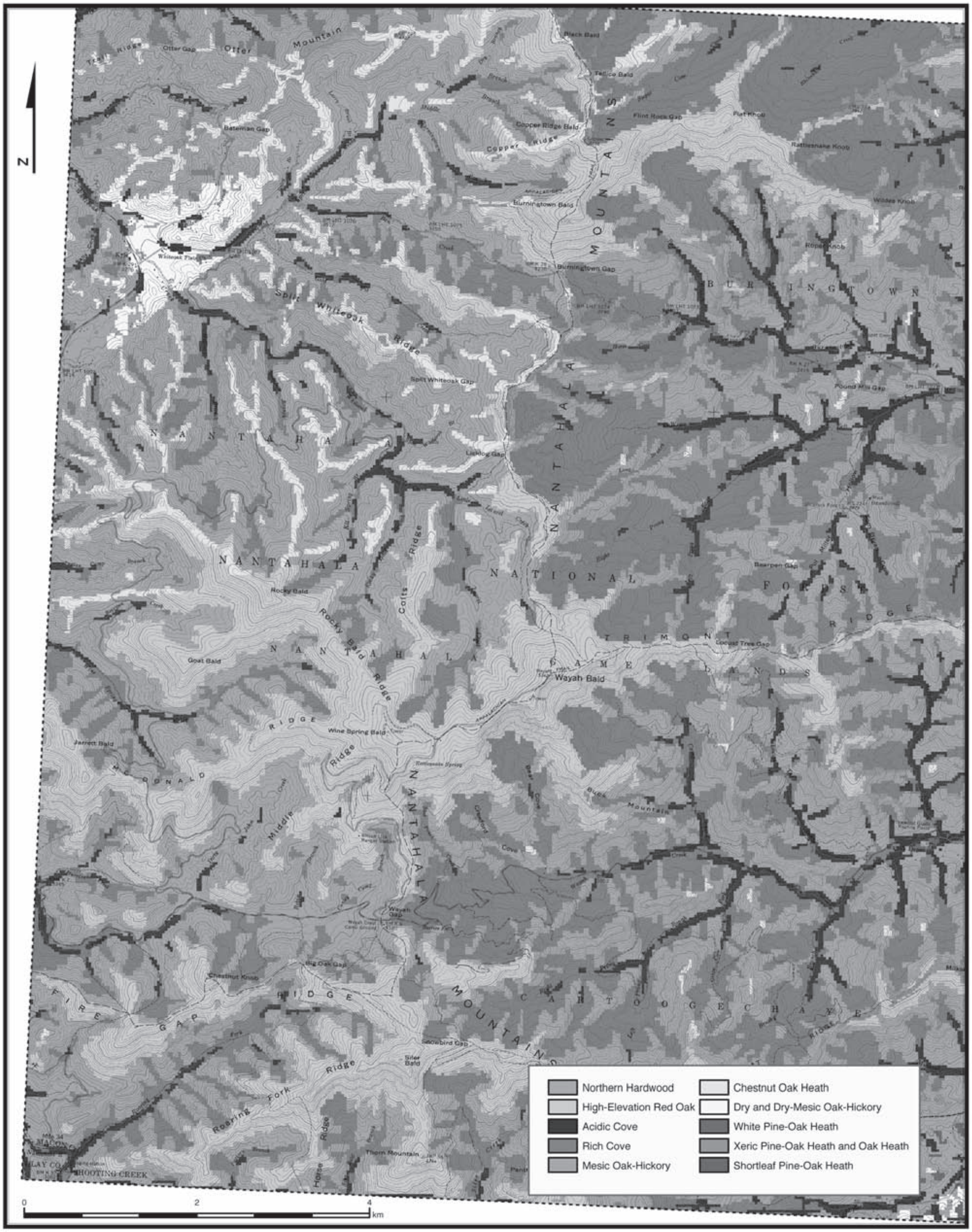

Figure 11—Predicted ecological zones of the Wayah Bald topographic quadrangle. (Available in color on CD-ROM inside the back cover.)

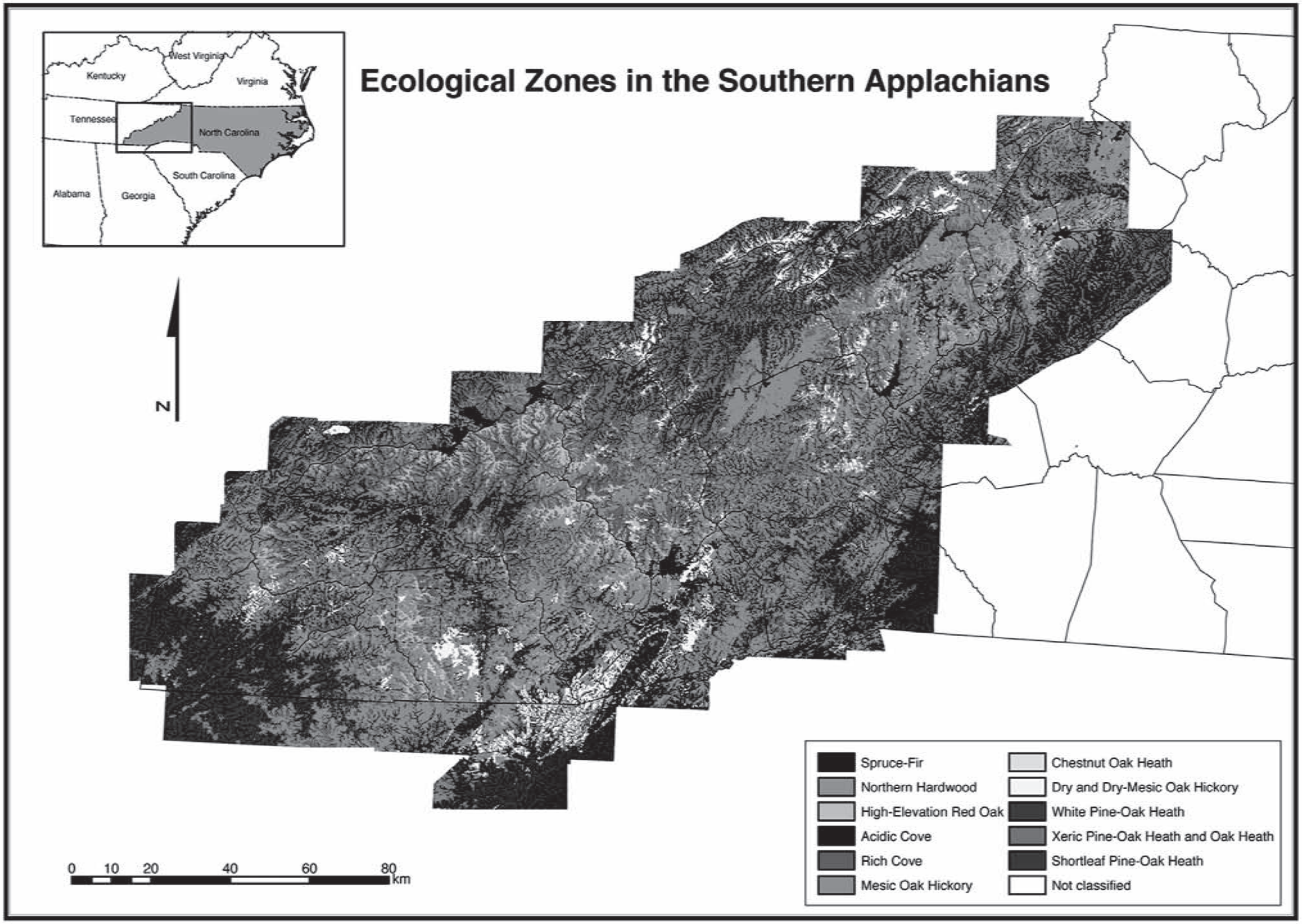

Figure 12—Predicted ecological zones of the Southern Appalachian Mountains study area in North Carolina. (Available in color on CD-ROM inside the back cover.)

Table 11—Ecological zones in the Southern Appalachian Mountains

Ecological zone	Total area		Federal land	
	no. acres	*percent*	*no. acres*	*percent*
Spruce-Fir	45,500	0.8	12,400	1.2
Northern Hardwood	197,000	3.5	48,800	4.8
High-Elevation Red Oak	142,000	2.5	45,600	4.5
Rich Cove	498,000	8.8	114,000	11.3
Acidic Cove	1,331,000	23.6	199,700	19.8
Mesic Oak-Hickory	1,772,000	31.4	302,300	30.0
Dry and Dry-Mesic Oak-Hickory	125,600	2.2	25,800	2.6
Chestnut Oak Heath	60,600	1.1	11,000	1.1
White Pine-Oak Heath	133,000	2.4	21,300	2.1
Xeric Pine-Oak Heath and Oak Heath	759,000	13.5	191,800	19.0
Shortleaf Pine-Oak Heath	452,000	8.0	22,100	2.2
Not classified	125,000	2.2	14,000	1.4
Total	5,640,700		1,008,800	

were correctly classified. More detail was evident from the field validation, however; the incorrectly classified plots were predominately Acidic Cove (70 percent), a type found in similar topographic situations. Only 3 percent were in significantly less mesic sites, indicating that the model was performing well in this portion of the moisture and temperature gradient, but less well for fertility.

Discussion

Results of this investigation suggest that the 11 hypothesized ecological zones based on plant communities developed by Ulrey (see footnote 3) are associated with unique sets of environmental variables. In comparison, Whittaker (1956) described 13 arborescent-dominated vegetation types in the western Great Smoky Mountains of Tennessee. Models developed for each of the 11 ecological zones generally confirmed the patterns of vegetation environment reported by earlier investigators in the Southern Appalachians. Elevation, geofertility, and average annual precipitation were the most important predictive variables reflecting the primary environmental gradients of temperature, fertility, and moisture, respectively. Weighted landform index, a measure of site protection that integrates components of temperature and moisture, and to some degree fertility, was the next most important predictive variable included in the models.

Landscape variables used in modeling, such as elevation and precipitation, are surrogates for environmental factors such as temperature, moisture, and fertility. The statistical significance of variables, however, does not imply cause-and-effect relationships. Their correlation often is unclear and interpretations are even more complex when interactions of variables occur within an ecological zone. Because the formulation of some models may have resulted from artifacts of the dataset used for analysis, and therefore were possibly overfitted with variables, our results should be considered as preliminary until tested with an independent dataset. Overfitting is a contributing factor for predictions from some models that appear to be biologically illogical.

Following elevation, lithologic classification was the next most important variable in the models. Lithologic variables generally were less important at high elevation than at lower elevations. Coefficient sign of the lithologic variable was logical for most models. For example, geologic formations of high base content were negatively related to the Acidic Cove Zone, but positively associated with Rich Cove. For some ecological zones, Xeric Pine-Oak Heath and Oak Heath for example, the positive association with lithologic group was likely a better indicator of soil texture and water-holding capacity than an indicator of fertility.

Our study was among the first attempts to quantify the relationship of geologic variables to the occurrence of vegetation, particularly as related to fertility and factors affecting soil-moisture relationships. The importance of the lithologic group characterized by high-base status was shown to be important in the distribution of two ecological zones (Rich Cove and Northern Hardwoods), which have been long thought associated with sites of higher fertility levels. In a similar, large-scale study of vegetation in the Southern Appalachians, Newell and others (1999) reported that Rich Cove forests were associated with sites of higher nutrient availability, as indicated by soil manganese levels.

A more detailed study of ecological zones would use more accurate geologic maps. For example, an ecological study made at a watershed scale would use geologic maps at least as detailed as 1:24,000 scale. In addition, a more detailed study of ecological zones probably would include additional geologic map units, such as surficial deposits. Those map units could be classified for fertility and, in some cases, may result in the addition of a new member to the eight fertility groups described in table 3. Surficial deposits such as colluvium and alluvium are part of the surface geology and may support locally more diverse plant communities (Hatcher 1980, 1988; Pittillo and others 1998). Hughes (1995) describes a general procedure for integrating geology into ecosystem studies, including consideration of geologic factors relating to fertility. In some regions of steep slope gradients, however, fertility of some sites may not be directly associated with the underlying rock formations because the soil probably has moved downhill from its parent material.

A logical explanation is not obvious for the importance of variables in some models. For example, both dormant-season and growing-season precipitation were included in four ecological zone models, but with different signs of coefficients. In each of the four models, the ecological zone was positively associated with growing-season precipitation but negatively associated with dormant-season precipitation. Also, because dormant-season precipitation is a part of total precipitation, its increase often is concurrent with a decrease in growing-season rainfall, which could explain the inverse relationships. Summer precipitation seems more important than winter precipitation. Conventional wisdom suggests that inclusion of the latter variable in some ecological zone models may simply be a spurious relationship.

The importance of geographical variables in over half of the ecological zone models suggests that such models may be lacking important environmental variables. For example, geographical variables may be acting as surrogates for effects of certain temperature regimes, such as length of growing season or perhaps a more complex relationship related to evapotranspiration. Geographic variable correlations also may be explaining even more complex biogeographic patterns influenced by past climates and plant community migrations. In all but one ecological zone model where a geographical variable was important, it was the second most important variable. Other explanations for the importance of geographical variables include past land use patterns and climatic influences.

The classification accuracy of individual ecological zone models is variable, ranging from 69 to 95 percent. Models with the highest accuracy are Shortleaf Pine-Oak Heath (95 percent) and Spruce-Fir (92 to 93 percent) Zones, which occur at opposite ends of the elevation range of the study area. The least accurate models are Mesic Oak-Hickory (69 percent) and Chestnut Oak Heath (77 percent). One reason for the low accuracy of the Chestnut Oak Heath Zone is that it can occur both on the dry brow of ridges and on moist lower slopes. Accuracy levels are moderate for the Xeric Pine-Oak Heath and Oak Heath, although this ecological zone is rather broadly mapped and does not separate important pine-oak communities from oak communities. Further study is needed to differentiate Table Mountain pine-oak and pitch pine-oak communities from oak-dominated communities within this zone.

Model accuracy can be affected by several factors: (1) DEM reliability, (2) resolution of geologic maps, (3) field plot density and landscape representation, (4) accuracy of plot location using GPS and especially latitude and longitude from topographic maps, and (5) the definition of ecological zones and the classification of plots into these zones. Increasing the number and distribution of field sample points and their representation of the landscape is an efficient means of increasing map resolution and accuracy, given the current ecological classification framework. One method of improving and testing model accuracy would be to supplement the existing dataset with additional observations, perhaps from later years when the North Carolina Vegetation Survey is sampled in the study area. Another method of accomplishing this objective involves classifying plant communities encountered in the field using a standardized dichotomous key, such as developed by Ulrey (see footnote 3), and recording the location using a GPS. The classified plant communities at these locations would be merged with the database of physical attributes as illustrated in figure 8. The new dataset could then be used to create a more robust model for ecological zones that would characterize landscape variation at a scale appropriate for smaller watershed- and local-project level analyses. Given the relatively low resolution and accuracy of available 30-m DEMs, modeling at a finer level of ecological zone classification currently appears impractical.

Ecological zones are a broad level of organization of the diverse Southern Appalachian landscapes. In addition to providing insight regarding environmental factors affecting the distribution of vegetation, ecological zones may be appropriately used for a number of purposes. For example, boundaries of ecological units displayed on existing small-scale ecoregion maps might be refined and evaluated. Also, ecological zones may provide a consistent and objective means of analysis and evaluation of management options proposed in periodic planning for national forest lands.

Our classification models have one obvious limitation—they define ecological zones for environments only in the Southern Appalachians Mountains in North Carolina. Although the mountains are present in five Southern States, environmental relationships important in North Carolina would likely differ elsewhere, particularly at more northern and southern latitudes. A less obvious problem in application of the models elsewhere is the lack of data for the lithologic groups used in our analysis. Although uniform DEMs are available for all of the Southern Appalachians, geologic unit classifications typically do not match in definition or detail across State boundaries. Rock units of other States, however, could be classified into lithologic groups similar to those used in our study (appendix C).

Conclusions

Results of this preliminary study suggest that distinct ecological zones in the Southern Appalachian Mountains can be objectively identified from plant community sampling associated with environmental variables using multiple logistic regression, and mapped using DEMs applied with a GIS. We found that plant communities derived from a previous classification have ecological meaning because each is associated with a unique set of environmental variables. We also found that geological formation, which was used as an indication of soil fertility, was an important environmental variable affecting the distribution of many ecological zones. Evaluation of model formulation should continue and additional environmental variables, such as temperature and growing-season length, should be included. We suggest that the ecological zones identified in this study could be used as a basis for subdividing the forested landscape into homogeneous units to provide a basis for planning at a range of scales and evaluation of proposed and implemented management activities.

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Appendix A

A hierarchical classification of vegetation in the Southern Appalachian Mountains of North Carolina[1] [2]

Major group	Ecological group	Ecological subgroup
Montane wetland (63)	Three groups[3] (63)	Five subgroups[3] (63)
Open upland vegetation (134)	Four groups[3] (134)	Eleven subgroups[3] (134)
Upland forests (2,035)	Acid mesic forests (287)	Acidic cove forests (184)
		Hemlock forests (103)
	Dry-mesic forests (769)	Calcareous dry-mesic forests (9)
		Chestnut oak forests (174)
		Oak-hickory forests (366)
		Mesic montane oak-hickory forests (220)
	Northern hardwood forests (296)	Beech gap and slope forests (6)
		Northern hardwood forests (112)
		Boulder field forests (31)
		High-elevation red oak forests (126)
		Yellow birch-spruce forests (21)
	Rich mesic forests (226)	Rich cove forests (226)
	Spruce and fir forests (70)	Fir forests (13)
		Spruce forests (42)
		Successional vegetation forests (15)
	Xeric forests (387)	Carolina hemlock forests (18)
		Shortleaf pine-oak forests (78)
		Table Mountain pine-pitch pine forests (159)
		Subxeric oak-pine forests (132)

[1] Ulrey, C.J. 1999. Classification of the vegetation of the Southern Appalachians. Report to the U.S. Department of Agriculture Forest Service, Asheville, NC. 88 p. Unpublished report. On file with: Southern Research Station, Bent Creek Experimental Forest, 1577 Brevard Road, Asheville, NC 28806. (Available on CD-ROM inside the back cover.)
[2] Number of plots are in parentheses following group and subgroup names.
[3] Subdivisions of these groups and subgroups are omitted because they were not used in this study.

Appendix B

Approach and Methods Used to Develop a Hierarchical Classification of Vegetation in the Appalachian Mountains of North Carolina[1]

The purpose of this project was to develop an objective classification of forest vegetation for the Southern Appalachian Mountains in North Carolina based on quantitative analysis of plot data. A combination of quantitative, multivariate methods was used to detect patterns of species composition. Methods included cluster analysis, indirect ordination, constancy, ordered tables, and indicator species analysis. The objective of this investigation was to group plots by widely recognized plant communities, in preparation for subsequent study of plant environment, or ecological, relationships.

A total of 2,232 plots were classified into 3 major groups: (1) montane wetlands (63 plots established in wet bogs and marshes); (2) open upland vegetation (134 plots in areas lacking a closed-tree canopy, such as grassy balds and rock outcrops); and (3) upland forests (2,035 plots with a largely closed canopy). The major groups of vegetation were subdivided into 13 smaller ecological groups of somewhat similar physiognomy and species composition consisting of 7 nonforest and 6 forest units. Finally, the ecological groups were subdivided into 35 ecological subgroups of relatively homogeneous species composition. The three-level classification of vegetation is presented in appendix A, with emphasis on the subgroups of closed-canopy forests, which were used in this study.

Results of the vegetation analysis were somewhat inconsistent with the knowledge of experts on how communities are organized in the region. A number of groups consisted of plots dominated by one or several species, e.g. Fraser fir, red spruce, Carolina hemlock, and readily matched widely recognized communities. Several groups of plots, however, were compositionally homogeneous, but appeared to be variants of oak-hickory or pine-oak heath forests and did not represent any recognized community. Because the scope of the study did not include identification and description of new plant communities, a quasi-subjective, knowledge-based classification was devised. The classification adopted includes components of widely used systems for North Carolina (Schafale and Weakley 1990) and the national vegetation classification (Grossman and others 1998). Although the lowest level in the devised classification is somewhat broader than that of plant community, it is sufficiently detailed to be useful for the original purpose of this study, for inventory, and provides a basis for future hypothesis testing.

[1] Ulrey, C.J. 1999. Classification of the vegetation of the Southern Appalachians. Report to the U.S. Department of Agriculture Forest Service, Asheville, NC. 88 p. Unpublished report. On file with: Southern Research Station, Bent Creek Experimental Forest, 1577 Brevard Road, Asheville, NC 28806. (Available on CD-ROM inside the back cover.)

Appendix C

Mapped geologic units (North Carolina Geological Survey 1985) classified by geofertility group[1]

Group	Map unit	Major group	Primary rock	Secondary rock
1	Yam2	Migmatitic biotite-hornblende gneiss	Amphibolite-hornblende	Feldspar
1	am	Sugarloaf Mountain rock unit	Amphibolite and hornblende gneiss	Cut by numerous pegmatite dikes
1	am	Northwest of Brevard fault zone	Amphibolite	—
1	am	Northwest of Brevard fault zone	Amphibolite and hornblende gneiss	—
1	am	Brevard fault zone	Amphibolite and hornblende gneiss	—
1	am	Northwest of Brevard fault zone	Amphibolite	—
1	am	Upper Precambrian-Lower Paleozoic	Amphibolite and hornblende gneiss	—
1	am	Blue Ridge	Amphibolite	—
1	am	Davidson River group	Amphibolite	—
1	am	Inner Piedmont	Amphibolite	—
1	am1	Biotite granitic gneiss	Amphibolite	—
1	am2	Biotite-hornblende migmatite	Amphibolite	—
1	bgb	Bakersville metagabbro and metadiabase	Metagabbro and metadiabase	—
1	bgb	East of Fork Ridge fault (Bakersville metagabbro)	Metagabbroid, original minerals highly altered (plagioclase and pyroxene in actinoline, etc.)	(Primary = plagioclase and pyroxene in actinoline, etc.)
1	bhg2	Biotite-hornblende migmatite	Biotite-hornblende gneiss	—
1	bhgb	Bakersville hyperstene metagabbro	Hyperstene metagabbro	—
1	bhgb	East of Fork Ridge fault (Bakersville metagabbro)	Hyperstene metagabbroid	—
1	bhm2	Biotite-hornblende migmatite	Biotite-hornblende-migmatite	Amphibolite, biotite-hornblende-gneiss
1	bogb	Bakersville metaolivine gabbro	Metaolivine gabbro	Grades outward to amphibolite
1	ck	Upper Precambrian-Lower Paleozoic	Mafic-ultramafic complex of Carroll Knob (amphibolite and hornblende gneiss)	(Primary = amphibolite and hornblende-gneiss)
1	ckg	Upper Precambrian-Lower Paleozoic	Metagabbro units at Carroll Knob complex (labradorite, hornblende)	(Primary = labradorite, hornblende)
1	cs1	Biotite granitic gneiss	Calc-silicate rock	Biotite granitic, amphibolite
1	cs2	Biotite-hornblende migmatite	Calc-silicate rock	Biotite hornblende migmatite
1	cs3	Aluminous metasedimentary	Calc-silicate rock	Diopside lenses
1	csam2	Biotite-hornblende migmatite	Amphibolite and calc-silicate rock	—
1	d	Middle Paleozoic	Diorite (dikes w/hornblende, plagioclase, biotite chorite)	Serpentine, muscovite-sericite, epidote, sphene, etc."
1	g	Paleozoic intrusive rocks	Gab. (olivine-pyroxene, pyroxene-hrnbln., ophitic plagiocla)	—
1	g	Upper Precambrian-Lower Paleozoic	Melagabbro and pyroxenite	(Augite, plagioclase, chlorite, muscovite, sphene, etc.)
1	ga	Unmetamorphosed intrusive rocks	Gab. - plagioclase, augite, hrnblnd., magnetite, hyperstene	—
1	gb	Northwest of Brevard fault zone	Metagabbro (pyroxene, horneblende, and plagioclase)	—
1	hbgg1	Biotite granitic gneiss	Hornblende-biotite gneiss	—
1	hbm1	Biotite granitic gneiss	Hornblende-biotite migmatite	Biotite granitic gneiss

continued

Mapped geologic units (North Carolina Geological Survey 1985) classified by geofertility group[1] (continued)

Group	Map unit	Major group	Primary rock	Secondary rock
1	hg	East of Fork Ridge fault (amphibole gneiss)	Hornblende gneiss	—
1	hgn	Metamorphosed rocks	Hornblende gneiss	—
1	hmg1	Biotite granitic gneiss	Hornblende-magnetite gneiss	Biotite granitie, amphibolite
1	hybh2	Biotite-hornblende migmatite	Hyperstene-biotite hornblende gneiss	—
1	pCaa	East of Fork Ridge fault (Ashe formation)	Amphibolite and amphibole gneiss	—
1	pCam	Blue Ridge	Amphibolite and hornblende gneiss	—
1	Trd	Unmetamorphosed intrusive rocks	Mafic dikes-plagioclase and pyroxene	—
1	Ybhg2	Migmatitic biotite-hornblende gneiss	Biotite hornblende gneiss	—
1	Ybhm2	Migmatitic biotite-hornblende gneiss	Undifferentiated group	—
1	Ycs2	Migmatitic biotite-hornblende gneiss	Calc-silicate granofels	Amphibolite, hornblende gneiss
1	Ygcs2	Migmatitic biotite-hornblende gneiss	Grossular-calc-silicate granofels	—
1	Ymg2	Migmatitic biotite-hornblende gneiss	Mafic granulite (hornblende)	—
1	Zaa	Ashe metamorphic suite	Layered amphibolite	—
1	Zaa	Ashe metamorphic suite	Layered amphibolite	Meta-calcareous sediments
1	Zacs	Ashe metamorphic suite	Calc-silicate granofels	Amphibolite, quartz-clinozoisite
2	m	Brevard fault zone	Marble	—
2	m	Brevard zone and southeast of Brevard zone	Marble (mostly calcite, in part dolomitic)	—
2	m	East of Fork Ridge fault (Ashe formation)	Marble	—
2	m	Inner Piedmont	Marble	—
2	pCcm	Blue Ridge	Very siliceous dolomitic marble	—
3	bg2	Biotite-hornblende migmatite	Biotite gneiss	Amphibolite, biotite hornblende
3	bg3	Aluminous metasedimentary	Biotite gneiss	Amphibolite, quartzite, calc-silicate
3	bgg1	Biotite granitic gneiss	Biotite granitic gneiss	Amphibolite, hornblende migmatite
3	bgn	Upper Precambrian-Lower Paleozoic	Biotite granitic gneiss	Lenses and bands of amphibolite, pods of pegmatite
3	ccr	Coweeta group (Coleman River formation)	Metasandstone and quartz-feldspar gneiss	Interlayered pelitic schist and calc-silicate quartzite
3	cmy	Brevard zone	Calcareous mylonite	—
3	cs	East of Fork Ridge fault (Ashe formation)	Calc-silicate rock (85 percent quartz and feldspar, 15 percent amphibole)	—
3	egg1	Biotite granitic gneiss	Epidote-veined granitic gneiss	Amphibolite, biotite gran. gneiss
3	egg2	Biotite-hornblende migmatite	Epidote-veined granitic gneiss	Hornblende migmatite and amphibolite
3	ggg	Great Smoky group (Grassy Branch formation - lower metamorphic)	Metasandstone with muscovite schist	Many beds with calcareous concretions up to 1 foot in diameter
3	ggn	Sugarloaf Mountain rock unit	Biotite-muscovite granitic gneiss	Cut by numerous pegmatite dikes, locally hornblende
3	gt	Thunderhead formation	Metasandstone with calcareous concretions 2 feet in size	Muscovite schist
3	hyp1	Biotite granitic gneiss	Hyperstene-plagioclase rock	Magnetite, hornblende, biotite
3	mbg2	Biotite-hornblende migmatite	Magnetite-biotite gneiss	Biotite hornblende migmatite
3	Ybag2	Migmatitic biotite-hornblende gneiss	Biotite augen gneiss	Migmatitic biotite-hornblende gneiss and amphibolite

continued

Mapped geologic units (North Carolina Geological Survey 1985) classified by geofertility group[1] (continued)

Group	Map unit	Major group	Primary rock	Secondary rock
3	Yhyp2	Migmatitic biotite-hornblende gneiss	Pyroxene granulite	Amphibolite, mafic granulite
3	Zabg	Ashe metamorphic suite	Biotite gneiss	Musc-bio-gneiss, calc-silicate, amp
3	Zaqc	Ashe metamorphic suite	Quartz-clinozoisite gneiss	Calc-silicate grano. and amphibolite
3	Zbgb	Intrusivie rocks	Bakersville metagabbro	Dikes
4	agg1	Biotite granitic gneiss	Augen granitic gneiss	Biotite granitic gneiss
4	agg1	East of Fork Ridge fault-aegirine granitic gneiss	Massive gneiss to protomylonite gneiss	—
4	ag	Southeast of Brevard fault zone	Augen gneiss	Minor biotite gneiss and schist
4	bag2	Biotite-hornblende migmatite	Biotite augen gneiss	Biotite hornblende migmatite
4	Cag	Cambrian	Augen gneiss (quartz monzonite composition)	—
4	Cag	Southeast of Brevard fault zone	Augen gneiss	—
4	cg	Northwest of Brevard fault zone	Cataclastic gneiss (granitic and biotite gneiss)	Locally includes biotite schist and amphibolite
4	cg	Brevard fault zone	Cataclastic gneiss (biotite and muscovite gneiss)	Biotite muscovite schist
4	cpc	Coweeta group (Persimmon Creek gneiss)	Quartz diorite gneiss	Interlayed with metasandstone, quartz-feldspar gneiss and peltic schist
4	DSwg	Whiteside intrusive suite	Foliated muscovite-biotite granitoid	—
4	DSwg	Paleozoic intrusive rocks-Pink Beds gneiss	Granodiorite to quartz monzonite of the Whiteside complex	—
4	DSwl	Paleozoic intrusive rocks-Looking Glass gneiss	Quartz diorite to granodiorite	—
4	gd	Metamorphosed rocks	Granodiorite	—
4	gg	East of Fork Ridge fault (granitic gneiss)	Massive gneiss to protomylonite	—
4	gg	Southeast of Brevard fault zone	Granitic gneiss (biotite granitic gneiss)	—
4	gg1	Biotite granitic gneiss	Granitic gneiss	Magnetite, sphene, biotite
4	hygg2	Biotite-hornblende migmatite	Hyperstene granitic gneiss	—
4	mag	East of Fork Ridge fault-aegirine granitic gneiss	Mylonite gneiss and protomylonite	—
4	mChg	Inner Piedmont	Mylonitic Henderson gneiss	(Mylonitic rocks derived from Henderson gneiss)
4	mgm	Middle Precambrian migmatic complexes	Banded gneiss and migmatite	Includes biotite quartz, geldspar gneisses, mica schist, minor quartzite
4	mgn2	Biotite-hornblende migmatite	Magnetite grantitc gneiss	Biotite hornblende migmatite
4	myg1	Biotite granitic gneiss	Mylonite (flaser) gneiss	Biotite granitic gneiss
4	Osgg	Ordovician-Silurian	Granitic gneiss	Interlayed with augen gneiss on eastern contact
4	OSgg	Southeast of Brevard fault zone	Granitic gneiss	—
4	pCc	Blue Ridge	Mylonitic quartz-feldspar gneiss	Minor amounts of garnet
4	pCtg	Unconformity	Toxaway gneiss (banded granitic gneiss)	—
4	pCwg	Grandfather Mountain window (Wilson Creek series)	Sheared granitic unit	—
4	pg	Middle Paleozoic	Pegmatite (quartz, plagioclase, microcline, muscovite)	Minor amounts of biotite, garnet
4	pg	Northwest of Brevard fault zone	Pegmatite (quartz, plagioclase, microcline, muscovite)	—

continued

Mapped geologic units (North Carolina Geological Survey 1985) classified by geofertility group[1] (continued)

Group	Map unit	Major group	Primary rock	Secondary rock
4	pg	Northwest of Brevard fault zone	Pegmatite and aplite bodies (plagioclase, microcline, quartz	Locally - garnet, tourmaline, aplite
4	pg	Northwest of Brevard fault zone	Pegmatite (quartz, plagioclase, microcline, muscovite)	—
4	pg	Whiteside intrusive suite	Pegmatite (microcline, albite-oligoclase, quartzite and muscovite)	—
4	pg	Northwest of Brevard fault zone	Pegmatite bodies (quartz, plagioclase, microcline, muscovite)	—
4	pgb	Pegmatite and trondhjemite	Pegmatite and trondhjemite	—
4	Pzp	Intrusive rocks	Pegmatite	Too small to depict at map scale
4	Pzt	Intrusive rocks	Trondhjemite-granodiorite	Mostly dikes
4	qfgf	Metamorphosed rocks	Quartzo-feldspathic granofels	Unmapped layers granitic gneiss, amphibolite, metaquartzite
4	Sogg	Inner Piedmont	Biotite granitic gneiss	—
4	t	Paleozoic intrusive rocks	Porphyritic trondhjemite with olioclase in quartz	—
4	t	Lower to Middle Paleozoic	Trondhjemite (plagioclase, plagioclase-quartz)	—
4	tg	Shining Rock group	Feldspathic gneiss and quartzite (ranges from metaarkose to orthoquartzite)	(Primary ranges from metaarkose to orthoquartzite)
4	Ymgn2	Migmatitic biotite-hornblende gneiss	Magnetite granitic gneiss	Migmatitic biotite hornblende gneiss
4	Ypgg2	Migmatitic biotite-hornblende gneiss	Porphyroclastic granitc gneiss	Biotite augen gneiss
5	as	East of Fork Ridge fault	Actinolite schist	—
5	as	Inner Piedmont	Schistose to massive actinolite-chlorite talc body	—
5	bg	Southeast of Brevard fault zone	Biotite gneiss	Minor amounts of biotite schist, amphibolite, augen gneiss
5	bg	Southeast of Brevard fault zone	Muscovite-biotite gneiss	—
5	bg	Southeast of Brevard fault zone	Biotite-muscovite gneiss	Thin layers of muscovite-biotite schist
5	bg	Inner Piedmont	Biotite gneiss	Minor interlayers of garnet-mica schist and amphibolite with hornblende gneiss
5	bggs	Shining Rock group	Biotic gneiss and garnet schist	—
5	bmg	Tallulah Falls formation (graywacke-schist	Biotite-muscovite gneiss and schist member)	Minor biotite-muscovite gneiss, mica schist, amphibolite
5	bmg	Davidson River group	Feldspathic mica gneiss	Thin bands of neosomal pegatite present
5	bpg	Tallulah Falls formation (graywacke-schist member)	Biotite-plagioclase-quartz gneiss	Minor amounts of metasandstone
5	bpg	Blue Ridge	Biotite paragneiss and schist	—
5	bw	Northwest of Brevard fault zone	Metasandstone and schist	Granitic and pegmatitc lenses, interbeded with mudstone, siltstone
5	bw	Northwest of Brevard fault zone	Biotite metasandstone	—
5	bw	Northwest of Brevard fault zone	Metasandstone and schist	Grades into metaconglomerate locally

continued

Mapped geologic units (North Carolina Geological Survey 1985) classified by geofertility group[1] (continued)

Group	Map unit	Major group	Primary rock	Secondary rock
5	cg	Tallulah Falls formation (graywacke-schist member)	Mylonite gneiss and mylonite schist	Muscovite
5	Ch	West of Fork Ridge fault (Hampton formation)	—	—
5	Chg	Brevard zone and southeast of Brevard zone	Henderson gneiss (augen gneiss)	Locally layers of mylonite
5	Chg	Inner Piedmont	Henderson gneiss (biotite augen gneiss)	—
5	Chg	Metamorphosed rocks	Henderson gneiss	—
5	crp	Coweeta group (Ridgepole Mountain formation)	Biotite-garnet schist, pelitic schist, metaorthoquartzite, metasand	—
5	cs	Northwest of Brevard fault zone	Muscovite-chlorite schist	Minor thin layers of metasandstone
5	cs	Metamorphosed rocks	Chlorite schist	—
5	Cul	West of Fork Ridge fault (Unicoi formation- lower)	Metaconglomerate: metatuff, greenstone, metamudstone	Interbedded with arkosic metasandstone and metasiltstone
5	Cuu	West of Fork Ridge fault (Unicoi formation - upper)	Conglomeratic metasandstone	Interbedded with quartzite and phyllitic metamudstone
5	cw	Northwest of Brevard fault zone	Metasandstone, metaconglomerate, and biotite-muscovite schist	—
5	cw	Northwest of Brevard fault zone	Metasandstone, metaconglomerate, and biotite-muscovite schist	—
5	fs	Brevard zone	Schistose mylonite and phyllonite	—
5	gam	Great Smoky group (Ammons formation)	Metasandstone with metasiltstone and muscovite schist	Minor calc-silicate granofels and porphyroblastic muscovite schist
5	gbb	Great Smoky group-Buck Bald formation	Graywacke metaconglomerate and slate and metasiltstone	—
5	gbgs	Great Smoky group-Boyd Gap formation	Feldspathic metagraywacke	Rare beds of graywacke metaconglomerate
5	gch	Great Smoky group-Copperhill formation	Metagraywacke	Interlayered with graywacke metaconglomerate, garnet muscovite schist
5	gdf	Great Smoky group (Dean formation)	Metasandstone, porphyroblastic muscovite schist	Minor metaquartzite, metasiltstone muscovite schist and calc-silicate
5	ggs	Great Smoky group (Grassy Branch formation -upper schist)	Porphyroblastic muscovite schist and metasandstone	Minor muscovite schist, calc-silicate granofels
5	gmg	East of Fork Ridge fault (granitic gneiss)	Mylonite gneiss facies (mylonitic gneiss and schist)	—
5	gms	Sugarloaf Mountain rock unit	Garnetiferous muscovite schist	—
5	gms	Northwest of Brevard fault zone	Garnetiferous muscovite schist	—
5	gms	Northwest of Brevard fault zone	Garnetiferous mica schist	Interlayered with minor amounts feldspathic metasandstone
5	gms	Northwest of Brevard fault zone	Garnet-mica schist	Interlayers of mica gneiss and feldspathic metasandstone
5	gms	Tallulah Falls formation (garnet-aluminous schist member)	Garnetiferous mica schist	—
5	gms	Inner Piedmont	Garnet-mica schist	Kyanite, oligoclase, ilmenite, chlorite

continued

Mapped geologic units (North Carolina Geological Survey 1985) classified by geofertility group[1] (continued)

Group	Map unit	Major group	Primary rock	Secondary rock
5	gms	Metamorphosed rocks	Garnet-muscovite-biotite schist	—
5	gs	Northwest of Brevard fault zone	Graphite-muscovite schist	—
5	Kakgs	Ashe metamorphic suite	Kyanite-garnet schist	Garnet-muscovite-biotite gneiss and metagrawacke
5	kgms	Metamorphosed rocks	Kyanite-garnet-muscovite-biotite schist	—
5	lgn	Northwest of Brevard fault zone	Layered biotite gneiss (biotite-plagioclase-quartz gneiss and biotite-muscovite gneiss, calc-silicate granofels)	—
5	mbg3	Aluminous metasedimentary	Muscovite-biotite gneiss	Biotite gneiss, metasubgraywacke
5	mg	Northwest of Brevard fault zone	Layered muscovite gneiss and schist	—
5	mg	Northwest of Brevard fault zone	Layered mica gneiss and schist	Interlayered with garnet-biotite-muscovite schist, biotite schist, etc.
5	mgn	Northwest of Brevard fault zone	Mica gneiss	Interlayers include biotite schist, metasandstone, mica schist
5	mmg	Southeast of Brevard fault zone	Mixed mica gneiss	—
5	mps	Blue Ridge	Muscovite-biotite paraschist	Grades into biotite schist, quartz biotite schist,
5	ms	Northwest of Brevard fault zone	Garnetiferous muscovite and muscovite-biotite schist	Minor amounts of metasandstone
5	ms	Northwest of Brevard fault zone	Mica schist	Interlayered with micaceous feldspathic metasandstone
5	ms	Northwest of Brevard fault zone	Mica schist	Garnet and muscovite interlayered with micaceous metasandstone
5	ms	Northwest of Brevard fault zone	Mica schist	Thin, conformable granitic or quartz-rich pegmatitic layers throughout
5	ms	Tallulah Falls formation (graywacke-schist member)	Muscovite schist and biotite-muscovite schist	Minor thin layers of biotite-plagioclase-quartz gneiss
5	ms/cg	Rocks of Kings Creek Valley	Mica schist and biotite gneiss	Includes cataclastic equivalent (cg) projected from Rosman quadrangle
5	mss	Upper Precambrian	Metasandstone and schist	—
5	my	Brevard fault zone	Porphyroclastic mylonite and ultramylonite	—
5	my	Brevard fault zone	Porphyroclastic mylonite	Grades to cataclastic schist and phyllonite
5	my	Brevard zone and southeast of Brevard zone	Porphyroclastic mylonite and ultramylonite	Interlayers of pophyroclastic phyllonite and phyllonitic schist
5	my	Inner Piedmont	Porphyroclastic mylonite and ultramylonite	—
5	my	Brevard fault zone	Porphyroclastic mylonite	Grades into cataclastic schist and phyllonite
5	pCags	East of Fork Ridge fault (Ashe formation)	Mica gneiss and schist	—
5	pCc	East of Fork Ridge fault (Cranberry gneiss)	Biotite gneiss and schist	—
5	pCcg	East of Fork Ridge fault (Cranberry gneiss)	Quartzo-feldspathic gneiss	Minor biotite
5	pCcm	East of Fork Ridge fault (Cranberry gneiss)	Mylonite gneiss inlayered with biotite schist and biotite mylonite gneiss	—
5	pCcs	East of Fork Ridge fault (Cranberry gneiss)	Biotite schist (biotite, clinozoisite and quartz)	—

continued

Mapped geologic units (North Carolina Geological Survey 1985) classified by geofertility group[1] (continued)

Group	Map unit	Major group	Primary rock	Secondary rock
5	pCwmg	Grandfather Mountain window (Wilson Creek series)	Mica gneiss to augen gneiss	—
5	pCwrg	West of Fork Ridge fault-granodiorite gneiss	Gneiss, numerous quartz veins and aplite dikes present	—
5	pCwrm	West of Fork Ridge fault-granodiorite gneiss	Mylonite gneiss facies (mylonite schist and quartzofeldspathic mylonite gneiss	(Primary = mylonite schist and quartzofeldspathic mylonite gneiss)
5	pgc	Davidson River group	Porphyroclastic mica gneiss	—
5	pgn	Northwest of Brevard fault zone	Biotite-plagioclase-quarzt gneiss	Interlayered with minor amounts of muscovite-biotite schist
5	pgn	Tallulah Falls formation (garnet-aluminous schist member)	Porphyroblastic biotite-muscovite gneiss	—
5	pgw	Northwest of Brevard fault zone	Paragneiss and metagraywacke	Interlayered biotite schist, metasandstone; garnet schist, phyllite
5	pgwb	Northwest of Brevard fault zone	Biotite metasandstone	Locally garnet
5	pmy	Metamorphosed rocks	Porphyroclastic mylonite schist and gneiss	—
5	qbgn	Metamorphosed rocks	Quartz-biotite-plagioclase gneiss	—
5	sbcgl	Snowbird group	Metaconglomerate alternates with arkosic metasandstone	Metasiltstone, slate, phyllite
5	sbss	Snowbird group	Metasandstone inbeded with metasiltstone, slate and phyllite	—
5	sbst	Snowbird group	Metasiltstone	Slate and phyllite
5	ssg	Tallulah Falls formation	Sillimanite schist and gneiss	—
5	tf	Tallulah Falls formation	Biotite paragneiss and schist	Interlayers of pelitic schist, metasandstone to metagraywacke
5	tw	Northwest of Brevard fault zone	Thin-layered metasandstone and schist	Schist locally contains graphite and garnet
5	Zag	Ashe metamorphic suite	Muscovite biotite gneiss	Kyanite-garnet schist, metagraywacke
5	Zagg	Ashe metamorphic suite	Garnet-muscovite-biotite gneiss	—
5	Zamy	Ashe metamorphic suite	Mylonitic muscovite-feldspar-quartz gneiss	—
5	Zaw	Ashe metamorphic suite	Metagraywacke	Schist, gneiss, calc-silicate metagraywacke
6	bmy	Brevard zone	Blastomylonite (augen of feldspar in mylonitic matrix)	—
6	Cc	Grandfather Mountain window (Chilowee group)	Quartzite (85 percent quartz)	—
6	Ce	West of Fork Ridge fault (Erwin formation)	Metasandstone and quartzite	Beds of conglomeratic metasandstone
6	my	Mylonite	—	—
6	my	Brevard zone	Mylonite	—
6	ntq	Nantahala formation	Metaquartzite with thin laminae of schist	Schist, metasiltstone
6	P	Paleozoic intrusive rocks	Pegmatite	Sills and pods of quartz and microcline
6	pCqq	Blue Ridge	Mylonitized leucocratic quartz monzonite	—
6	Pcwq	Grandfather Mountain window (Wilson Creek series)	Quartz monzonite unit	Cataclastic textures range from mortar gneiss to mylonite throughout
6	pg	Unmetamorphosed intrusive rocks	Pegmatite - quartz, plagioclase, microcline, muscovite, biotite	—

continued

Mapped geologic units (North Carolina Geological Survey 1985) classified by geofertility group[1] (continued)

Group	Map unit	Major group	Primary rock	Secondary rock
6	q	Upper Precambrian	Quartzite (massive metaorthoquartzite)	Metagraywacke and metaconglomerate
6	q	Blue Ridge	Quartzite	Muscovite and microcline
6	qm	Brevard zone	Quartz monzonite	—
6	qv	East of Fork Ridge fault	Quartz veins	Minor sericite
7	bpu	Inner Piedmont	Brecciated phyllonite and ultramylonite	(Primary = carbonaceous phyllonite, ultramylonite, porphyroclas)
7	fs	Brevard fault zone	Cataclatic schist, phyllonite, and mylonite	Some layers of calcite
7	fs	Brevard fault zone	Cataclastic schist, phyllonite, and mylonite	—
7	fs	Brevard fault zone	Phyllonite, cataclastic schist, and mylonite	Garnet, chlorite, muscovite locally
7	fs	Brevard zone and southeast of Brevard zone	Porphyroclastic phyllonite and phyllonitic schist	—
7	fs	Inner Piedmont	Porphyroclastic phyllonite and phyllonitic schist	—
7	ga1	Anakeesta formation (lower black schist unit)	Muscovite schist, metasandstone	—
7	ga2	Anakeesta formation (lower metasandstone unit)	Metasandstone facies but with schist and muscovite schist	—
7	ga3	Anakeesta formation (middle black schist unit)	Schist	Metasandstone
7	ga4	Anakeesta formation (upper metasandstone unit)	Metasandstone facies but with schist and muscovite schist	—
7	ga5	Anakeesta formation (upper black schist unit)	Muscovite schist	Metasandstone
7	gbg	Great Smoky group-Boyd Gap formation	Slate and metasiltstone-very heterogeneous (notably sulfurous and graphitic)	(Primary = notably sulfurous and graphitic)
7	gf	Great Smoky group-Slaty unit	Sulfidic phyllite	Interlayered with feldspathic metagraywacke highly metamorphosed
7	ghb	Great Smoky group (Ammons formation, Horse)	Sulphidic mica schist and metasiltstone	Interbeded with metasandstone, metasiltstone, muscovite schist
7	gw	Great Smoky group-Wehutty formation	Sulfidic pyllitite and muscovite schist	Interlayered with slate and garnet-muscovite schist
7	nt	Nantahala formation	Sulphidic schist with quartzose metasiltstone	Metaquartzite
7	sms/ams	Davidson River group	Sulfidic muscovite schist	Thinly interlayered with amphibolite in portions
8	ckum	Upper Precambrian-Lower Paleozoic	Ultramafic unit at Carroll Knob complex (dunite, soapstone, serpentinite)	(Primary = dunite, soapstone, serpentinite)
8	du	Dunite	—	—
8	um	Southeast of Brevard fault zone	Altered ultramafic rock	—
8	um	Northwest of Brevard fault zone	Altered ultramafic rock	—
8	um	Northwest of Brevard fault zone	Altered ultramafic rock	—
8	um	Upper Precambrian-Lower Paleozoic5	Ultramafic rocks	—
8	um	Blue Ridge	Altered ultramafic rock	—
8	um	Paleozoic intrusive rocks	Ultramafic rock (olivine, peridotite, bronzitite, talc schist)	—
8	Zud	Intrusive rocks	Dunite	Unaltered = olivine, altered = serpentinite

— = no data.

[1] Collins, T.K. Geo-fertility groups in the Southern Appalachians. Unpublished document. 2 p. with attachments. On file with: George Washington and Jefferson National Forests, 5162 Valleypointe Parkway, Roanoke, VA 24019–3050.

Appendix D

Variables in the Southern Appalachian digital elevation database

Landscape Characterization Variables

Dormant-season rainfall: October to April average precipitation in inches, based on a 30-year average orographic effects model. Cell size was originally 1,000 feet by 1,000 feet.

Growing-season rainfall: May to September average precipitation in inches, based on a 30-year average, orographic effects model. Cell size was originally 1,000 feet by 1,000 feet.

Landform Characterization Variables

Landform index: index of landform shape (site protection) and macroscale landform.

Weighted landform index: landform index weighted by aspect using northeast (45°) as the reference aspect; as above but considers direction-sheltering influence (ridges).

Landform shape8: average elevation change in an 8 by 8 grid of neighboring digital elevation data cells (find maximum elevation in a 3 by 3 grid of cells; subtract elevation from this maximum; focal mean on the elevation difference in the 8 by 8 grid).

Landform shape16: average elevation change in a 16 by 16 grid of neighboring digital elevation data cells (find maximum elevation in a 3 by 3 grid of cells; subtract elevation from this maximum; focal mean on the elevation difference in the 16 by 16 grid).

Landform index surface interaction: interaction between landform index and surface curvature quantified by Environmental Systems Research Institute algorithm Procurve (landform index multiplied by Procurve).

Weighted landform index surface interaction: interaction between weighted landform index and surface curvature (weighted landform index multiplied by Procurve).

Length of slope: total slope segment length (from ridge to valley, Euclidean distance).

Slope position: position along a slope segment (0 = ridge, 1 = valley).

Distance to bottom: distance to the valley bottom of the slope segment.

Distance to intermittent stream: distance to the closest intermittent stream (modeled first-order streams).

Slope direction: aspect (cosine of aspect) of plot calculated by Environmental Systems Research Institute algorithm.

Site Characterization Variables

Elevation: elevation from 30-m digital elevation model with sinks filled (converted to feet).

Terrain shape index: surface shape in 3 by 3 grid of neighboring DEM cells (convex = negative, concave = positive).

Surface curvature profile: curvature of surface in the direction of slope, Environmental Systems Research Institute variable calculated from 3 by 3 grid of cells.

Surface curvature planiform: curvature of surface perpendicular to slope, Environmental Systems Research Institute variable calculated from 3 by 3 grid of cells.

Curvature: Environmental Systems Research Institute variable calculated from 3 by 3 grid of cells (like terrain shape index).

Slope steepness: steepness of slope in percent using Environmental Systems Research Institute algorithm.

Slope steepness and slope position interaction: interaction of slope steepness and slope position (focal mean in 3 by 3 grid of slope times focal mean in 3 by 3 grid of slope position).

Geologic fertility group:[1] geology-fertility classes identified from 100 bedrock geology or lithology types: (1, 2) = high bases mafic and carbonate rock; (3) = low-base dominant rocks with inclusions of high-base; (4) = low-base granitic rocks; (5) = low-base sedimentary and metamorphic rock; (6) = low-base quartzitic rock; (7) = low-base sulphidic rock; and (8) = ultramafic rock. Geologic formations in the study area classified by geofertility group are listed in appendix C.

Geographic Characterization Variables

x geographic coordinants of plot location: distance east or west.

y geographic coordinants of plot location: distance north or south.

Distance from Murphy, NC: straight-line distance of plot from the extreme southwestern corner of North Carolina.

Distance from the Blue Ridge Escarpment: minimum straight-line distance from the escarpment.

[1] Collins, T.K. Geo-fertility groups in the Southern Appalachians. Unpublished document. 2 p. with attachment. On file with: George Washington and Jefferson National Forests, 5162 Valleypointe Parkway, Roanoke, VA 24019–3050.

Appendix E

Common and scientific names of flora referenced in the text

Common name	Scientific name	Common name	Scientific name
Table Mountain pine	*Pinus pungens*	White oak	*Quercus alba*
Oak-hickory	*Quercus-Carya*	Flowering dogwood	*Cornus florida*
Southern red oak	*Quercus falcata*	Canada richweed	*Collinsonia canadensis*
Yellow pines	*Pinus* spp.	Pignut hickory	*Carya glabra*
Yellow-poplar	*Liriodendron tulipifera*	Rattlesnakeroot	*Prenanthes* spp.
Northern red oak	*Q. rubra*	Sourwood	*Oxydendrum arboreum*
Red spruce	*Picea rubens*	Scarlet oak	*Quercus coccinea*
Fraser fir	*Abies fraseri*	Giant cane	*Arundinaria gigantea*
Red maple	*Acer rubrum*	Blackgum	*Nyssa sylvatica*
Bear huckleberry	*Gaylussacia ursina*	Pitch pine	*Pinus rigida*
Common stonecrop	*Sedum ternatum*	Black huckleberry	*Gaylussacia baccata*
Northern bush honeysuckle	*Diervilla lonicera*	Trailing arbutus	*Epigaea repens*
American chestnut	*Castanea dentata*	Maleberry	*Lyonia ligustrina* var *ligustrina*
American ginseng	*Panax quinquefolius*		
Yellow birch	*Betula alleghaniensis*	Shortleaf pine	*Pinus echinata*
American mountain-ash	*Sorbus americana*	Sand hickory	*Carya pallida*
Mountain woodfern	*Dryopteris campyloptera*	Post oak	*Quercus stellata*
Pennsylvania sedge	*Carex pensylvanica*	American holly	*Ilex opaca*
Mountain woodsorrel	*Oxalis montana*	Fire cherry	*Prunus pensylvanica*
Hobblebush	*Viburnum lantanoides*	Catawba rhododendron	*Rhododendron catawbiense*
Mountain holly	*Ilex montana*	Roan snakeroot	*Ageratina altissima* var. *roanensis*
Allegheny serviceberry	*Amelanchier laevis*		
American beech	*Fagus grandifolia*	Speckled wood-lily	*Clintonia umbellulata*
Sugar maple	*Acer saccharum*	Hemlock	*Tsuga* spp.
Canadian woodnettle	*Laportea canadensis*	Canada hemlock	*T. canadensis*
Wild leeks or ramps	*Allium tricoccum*	Black birch	*Betula lenta*
Flame azalea	*Rhododendron calendulaceum*	Heartleaf species	*Hexastylis* spp.
Whorled yellow loosestrife	*Lysimachia quadrifolia*	Mountain doghobble	*Leucothoe fontanesiana*
Highbush blueberry	*Vaccinium corymbosum*	Common greenbrier	*Smilax rotundifolia*
Mountain laurel	*Kalmia latifolia*	Black cohosh	*Actaea racemosa*
New York fern	*Thelypteris noveboracensis*	Mandarin	*Prosartes lanuginosa*
Partridgeberry	*Mitchella repens*	Dutchman's pipe	*Aristolochia macrophylla*
Great laurel	*Rhododendron maximum*	Mountain sweet-cicely	*Osmorhiza claytonii*
Heartleaf species	*Hexastylis* spp.	Appalachian basswood	*Tilia americana* var. *heterophylla*
Eastern white pine	*Pinus strobus*		
Blue cohosh	*Caulophyllum thalictroides*	Chestnut oak	*Quercus prinus*
Bloodroot	*Sanguinaria canadensis*	Galax	*Galax urceolata*
Northern maidenhair fern	*Adiantum pedatum*	Hillside blueberry	*Vaccinium pallidum*
Rattlesnake fern	*Botrychium virginianum*	Wintergreen	*Gaultheria procumbens*
Yellow buckeye	*Aesculus flava*	Featherbells	*Stenanthium gramineum*
White ash	*Fraxinus americana*	Spring iris	*Iris verna*

Source: Kartesz (1999).

Simon, Steven A.; Collins, Thomas K.; Kauffman, Gary L.; McNab, W. Henry; Ulrey, Christopher J. 2005. Ecological zones in the Southern Appalachians: first approximation. Res. Pap. SRS-41. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 41 p.

Abstract—Forest environments of the Southern Appalachian Mountains and their characteristic plant communities are among the most varied in the Eastern United States. Considerable data are available on the distribution of plant communities relative to temperature and moisture regimes, but not much information on fertility as an environmental influence has been published; nor has anyone presented a map of the major, broad-scale ecosystems of the region, which could be used for planning and management of biological resources on forestlands. Our objectives were to identify predominant ecological units, develop a grouping of geologic formations related to site fertility, and model and map ecological zones of the Southern Appalachians. We synthesized 11 ecological units from an earlier analysis and classification of vegetation, which used an extensive database of over 2,000 permanent, 0.10-ha, intensively sampled plots. Eight lithologic groups were identified by rock mineral composition that upon weathering would result in soils of low or high availability of base cations. The presence or absence of ecological zones (large areas of similar environmental conditions consisting of temperature, moisture, and fertility, which are manifested by characteristic vegetative communities) were modeled as multivariate logistic functions of climatic, topographic, and geologic variables. Accuracy of ecozone models ranged from 69- to 95-percent correct classification of sample plots; accuracy of most models was > 80 percent. The most important model variables were elevation, precipitation amount, and lithologic group. A regional map of ecological zones was developed by using a geographic information system to apply the models to a 30-m digital elevation dataset. Overall map accuracy was refined by adjusting the best probability cut levels of the logistic models based on expert knowledge and familiarity of the authors with known ecological zone boundaries throughout the study area. Preliminary field validation of an uncommon fertility-dependent ecological zone (Rich Cove) indicated a moderate, but acceptable level of accuracy. Results of this project suggest that bedrock geology is an important factor affecting the distribution of vegetation. The developed map is a realistic depiction of ecological zones that can be used by resource managers for purposes ranging from broad-scale assessment to local-scale project planning.

Keywords: Classification, ecosystems, fertility, geologic formations, logistic regression, moisture, multivariate analysis, ordination, temperature.