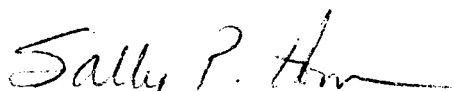
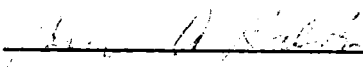


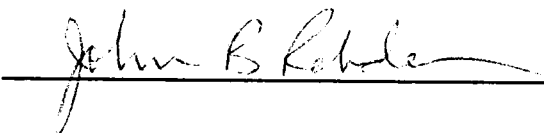
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IDENTIFICATION OF TEMPERATE RAINFOREST ENVIRONMENTS
IN THE SOUTHERN APPALACHIANS

A Thesis
Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

Michael J. Daly

December, 1993

DEDICATION

This thesis is dedicated to my family:

for my parents

William J. Daly and Gloria B. Daly

for their love and support,

for my sister

Jeanne M. Daly

for her constant encouragement,

for my brother

Christopher J. Daly

who first taught me about the temperate rainforest,

and for my Grandmother

Mary A. Ball

whose love of God's creation taught me

to appreciate nature from the earliest age

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ABSTRACT

The natural vegetation of the Southern Appalachian region included exceptional cove forests exhibiting characteristics typically associated with temperate rainforest formations. Human impacts over the past few centuries have almost completely eliminated these exceptional forests. The distribution of environments capable of supporting these forests is controlled regionally by climate, and locally by topography.

The Thornthwaite climatic classification is applied in the context of a GIS to identify the regional extent of the temperate rainforest (perhumid) climate under both average and drought conditions. A GIS database incorporating manually-derived topographic data and land use and forest vegetation data derived from a 1990 Landsat Thematic Mapper (TM) satellite image is developed for a local study area. The local GIS database is analyzed to determine if a spectral signature can be identified from the TM image that can be used to identify temperate rainforest environments.

The perhumid climate area of the region covers approximately 5200 square miles and persists, though reduced in extent, even during extreme drought conditions. Twenty percent of the local study area is characterized by topographic sites favorable to the development of temperate rainforest communities. Analysis of the selected TM image did

not identify a spectral signature that could be used to identify temperate rainforest environments. Extrapolation of the results from the local study area to the broader region suggests that 1000 square miles of the Southern Appalachian region are temperate rainforest environments. The conservation and restoration of the Appalachian temperate rainforest formation will contribute significantly to maintaining the biodiversity of the region.

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CHAPTER 1

INTRODUCTION

1.1 Overview

The natural vegetation of the Southern Appalachian mountains included areas of forest having exceptional quality in relation to the variety of species, mature size of trees, and longevity of trees (Braun, 1950; Shanks, 1954; Whittaker, 1956; Jackson, 1989; Houk, 1993). In general, the best examples of these forests were found locally in coves and on moist slopes, and were thus termed cove forests. Coves are topographic features characterized by gently sloping convex recesses along the sides of mountains. They typically are drained by a stream, are surrounded on three sides by steeper uplands, and have deep soils. Commercial exploitation of these exceptional forests proceeded without regulation into the early part of the 20th century, almost completely depleting them. The few remnants that still exist all occur in locations of heavy annual rainfall. Using 14,000 individual soil moisture readings over a seven year period at the Coweeta Hydrological Laboratory, Helvey and Hewlett (1961) concluded that vegetation within the high rainfall belt of the Southern Appalachians seldom experiences true drought conditions. Plant geographers commonly use the term "rainforest" to describe the vegetation that develops in areas of heavy annual rainfall where drought conditions seldom

occur. These areas are encountered most frequently in the tropics, where the natural vegetation develops into a dense, multi-canopied forest of tall trees. The Appalachian cove forests similarly develop a dense, multi-canopied forest structure of tall trees that is not unlike the tropical rainforest. Is "temperate rainforest" a valid designation for the remnant cove forests in the Southern Appalachians? What is the spatial distribution of the high rainfall belt with which these special forests seem associated?

Interestingly, one remaining forest area that might fit the temperate rainforest ideal, the Joyce Kilmer Memorial Forest in western North Carolina, has been cited as an example of the nation's "virgin wilderness" (U.S. Forest Service, n.d.). How likely is it that forests of comparable quality once comprised a significant portion of the eastern wilderness? Climatic variables, especially precipitation, exert a strong control on the regional distribution of forest vegetation (McNab, 1987). How many areas of the eastern forest region receive similar amounts of precipitation to the Southern Appalachian Region? Is the Joyce Kilmer Memorial Forest (JKMF) representative of a temperate rainforest formation that is a product of a spatially restricted Southern Appalachian temperate rainforest climate? Would any other locations in the eastern United States have had a similar character to the JKMF's "virgin wilderness"?

This thesis considers how one might determine the limits

of the temperate rainforest environment in the Southeastern U.S. Although several attempts have been made to classify climates and vegetation in the region, the possible existence and extent of a temperate rainforest environment has received little explicit attention. Lindsey and Sawyer (1970) analyzed climatic data from 1400 stations that were organized into eight groups based on forest regions of North America as defined by Braun (1950). The climatic variables from each station were plotted according to the Holdridge (1967) life zone model. This climate-based model includes a category for temperate rainforest. Considerable overlap was discovered between the different forest regions, especially the Appalachian Oak and Mixed Mesophytic regions. Despite the fact that climate exerts a strong control on vegetation patterns, this climate-based model was unable to effectively describe the observed variations in the distribution of forest regions. In addition, the Holdridge life zone model distinguishes between temperate wet forest and temperate rainforest climate regimes, but it is unclear if corresponding differences in vegetation exist between these two regimes. Thus, the Holdridge model is unlikely to determine the limits of temperate rainforest climate or vegetation in the context of eastern North America.

Barnes (1991) recognized that no single climatic classification is easily applicable to the analysis of regional forest ecosystems. He also recognized that

noticeable differences in community composition at the local scale were a function of variations in topography, soil, and disturbance history. These observations suggest that efforts to identify a Southern Appalachian temperate rainforest must overcome two primary obstacles. First, at a regional scale there is no climatic classification system that is easily applicable. Second, at the local scale the task requires an enormous volume of data (i.e., slope, aspect, soil, disturbance history), some of which may not be readily available.

Cognizant of these obstacles, this thesis seeks an heuristic solution to the problem of identifying temperate rainforest environments within the Southern Appalachian region. Two strategies are employed. First, the limits of the "high rainfall belt" are established at the regional scale by the application of the Thornthwaite (1931) Precipitation Efficiency Index (PE Index). Simple measures of rainfall alone are not sufficient for determining the limits of the rainforest. The supply of moisture from rainfall must be compared to the demand for moisture from evapotranspiration. On an annual basis, rainforests have a significant surplus moisture supply in comparison to moisture demands. A climate characterized by such a continuous surplus of moisture is termed perhumid. The Thornthwaite PE Index provides a quantitative measure of moisture conditions that distinguishes perhumid conditions. The PE Index is applied within the

context of a Geographic Information System (GIS) for both average conditions and drought conditions.

Shanks (1954) previously applied two of Thornthwaite's climatic classification systems (Thornthwaite 1931, 1948) to four weather stations in the Great Smoky Mountains National Park. It was found that both of the Thornthwaite systems identified significant changes in climate that corresponded well to observed changes in vegetation. He also reported that a rainforest or perhumid climate existed above approximately 2000 ft.

The Thornthwaite system is not inherently easy to apply. An excessive volume of complex computations is required for its successful application. In addition, calculation of the moisture index values require both temperature and precipitation data, so that at the regional scale, the number of stations that can be included are limited by the availability of temperature data. The use of GIS technology overcomes this first obstacle, by facilitating rapid calculations of input data, and the incorporation of modeled climatic data for missing empirical data values. Thus, GIS allows a Thornthwaite climatic classification system to be easily applied in this thesis project.

The second strategy involves a focused attempt to identify temperate rainforest environments within a local study area that is representative of the broader region. Results from this local study area are extrapolated to a

larger perhumid region, to estimate the potential area of temperate rainforest vegetation in the Southern Appalachians. This second strategy involves two steps. First, the topographic settings favorable for the development of temperate rainforest vegetation are derived manually from USGS topographic maps, digitized, and incorporated into the GIS of the local study area. The topographic situation of cove forests within smaller valleys and on moderate slopes with northern or eastern aspects has been widely reported (Ayres and Ashe, 1903; Holmes, 1911; Cain, 1943; Braun, 1950).

While incorporation of topographic information as a data layer is a fairly routine procedure for a GIS, the optimal solution to determine the location and area of topographic sites for the whole region requires the development of a detailed digital database that contains topographic, soil, geologic, and land use data. The costs (both time and money) of such an extensive database prohibits its actual development. Typically, database development is the single most expensive cost component of GIS projects and effectively limits the application of GIS technology to regional scale problems that transcend jurisdictional authority of individual state and government agencies. Thus, there is an acute need to investigate alternative techniques that can achieve the accuracy of full scale database development while minimizing the development costs.

The second step of the thesis research involves the use

of remotely sensed satellite data to determine if a spectrally significant signature identifies temperate rainforest environments. Meyer and Werth (1990) pointed out the increasing potential of incorporating satellite data into studies of natural resources over extensive land areas. Darch (1985) recognized the value of high resolution Landsat data for mapping smaller vegetation formations at a large scale. Landsat Thematic Mapper (TM) imagery was acquired for the local study area, and classified in terms of land use and vegetation types using ERDAS digital imaging processing software. The digital maps derived from the satellite data were combined with the climatic and topographic data in the GIS. The GIS was then used to analyze the variation in spectral signatures between previously identified temperate rainforest environments and non-temperate rainforest environments for the local study area. The identification of distinct spectral signatures for the temperate rainforest sites was expected to facilitate rapid and economical identification of temperate rainforest environments from satellite imagery of the broader region.

This effort to identify temperate rainforest environments through the application of GIS and remote sensing technology differs significantly from previous studies. For example, in the western United States, the U.S. Forest Service has successfully inventoried and mapped existing forests using both remotely sensed and ancillary data in a GIS context

(Green, 1990; Congalton et al., 1993). Most studies involving GIS and remote sensing have focused on mapping and analysis of existing vegetation (Jensen and Hodges, 1985; Cosentino et al., 1991; Fiorella and Ripple, 1993).

Some recent studies have used GIS to address potential vegetation based on predictive models (Polzer et al., 1991) and topographic gradients (Walker et al., 1992), but these used study areas of limited spatial extent. Also, the Walker et al. (1992) model of potential vegetation, which generated a synthetic raster image, was based on qualitative assumptions of moisture conditions from earlier ecological studies. Thus, the generated synthetic image, while technically a quantitative digital product, was in essence a qualitative description of expected vegetation patterns.

1.2 Structure of the Thesis

This thesis is divided into six chapters. Following this introduction, Chapters Two and Three describe the biogeographic context of the thesis project. Chapter Two examines the Southern Appalachian region, in relation to vegetation patterns, environmental history, and biological conservation. Chapter Three reviews rainforest in general, and temperate rainforests in particular. The temperate rainforest concept is refined via a careful examination of the unifying character of vegetation features and climatic characteristics associated with this formation. Chapter Four

presents the methods used to develop the regional climatic database and calculate the Precipitation Efficiency Indices. It also details the local database development process including the derivation of the digital topography layer and the image processing techniques used to develop digital maps of land use and vegetation types for the local study area from Landsat TM satellite imagery. Chapter Five reports the results of the study, and chapter Six discusses the results and draws conclusions concerning the extent of temperate rainforest environments within the Southern Appalachian region.

CHAPTER 2

THE FORESTS OF THE SOUTHERN APPALACHIAN REGION

2.1 Southern Appalachian Region

In the broadest sense, the Southern Appalachian region would include all territories of the four major Appalachian physiographic provinces (the Cumberland Plateau, the Valley and Ridge, the Blue Ridge, and the Piedmont) that are located south of Pennsylvania and Ohio. For the purposes of this study, the designation will refer only to the area of the Blue Ridge physiographic province south of the 36th parallel, which includes mountainous areas in Georgia, Tennessee, North Carolina and South Carolina (Figure 2.1). Thus defined, the Southern Appalachian region is comprised of two main mountain ranges, the Unakas and the Blue Ridge, both of which trend from the northeast to the southwest, and several smaller mountain ranges that cross the area between them. Elevations range from approximately 1200 feet in North Georgia up to 6684 feet at Mt. Mitchell, North Carolina. Most of the land surface is characterized by steep slopes, with level or nearly level land limited to ridge crests and narrow valleys and coves adjacent to streams. A notable exception to this generalization is the presence of several broader basins along the largest rivers. Examples include the Asheville Basin along the Swannanoa River and the Franklin Basin along the Little Tennessee River.

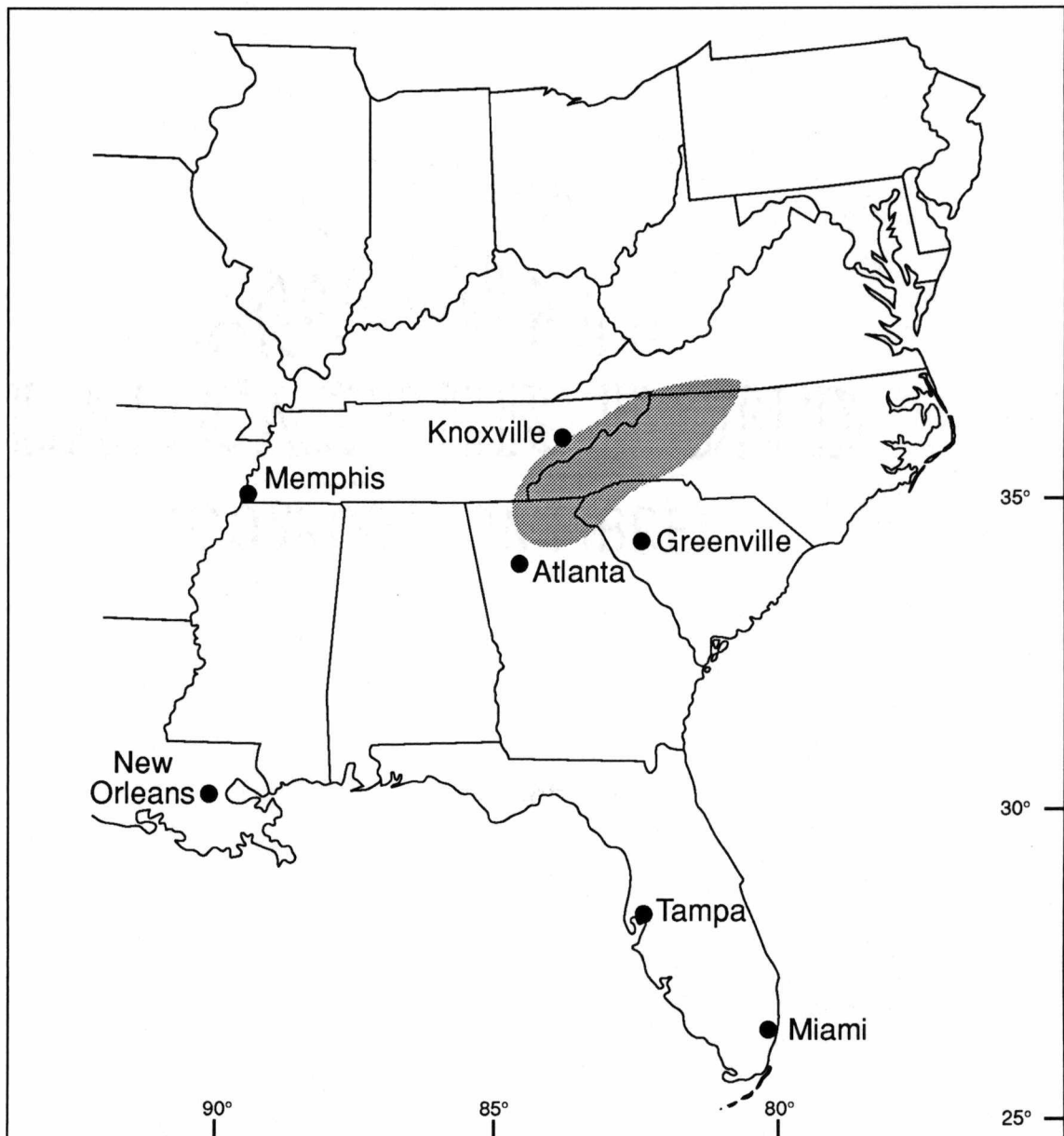


Figure 2.1 The Southern Appalachian Region

The climate is warm and humid with relatively mild winters. As is typical of mountainous areas, temperatures vary significantly with elevation. Precipitation is well distributed throughout the year with maxima occurring in January and July. Often there is a pronounced dry period in the late summer and early autumn. Precipitation varies greatly across the region. For example, Asheville, North Carolina is one of the driest stations east of the Mississippi river, whereas Highlands, North Carolina (only 52 miles away), is one of the wettest. Rainfall totals at Highlands are in fact surpassed within the continental U.S. only at certain sites in the Pacific Northwest.

2.2 Natural Vegetation

The natural vegetation of the Southern Appalachian region is principally forest except on high elevation balds, where open areas of shrubs and herbs may be the natural plant cover (Whittaker, 1956). At the continental level, the native forests of the region may be divided into two broad formations, the boreal coniferous forest formation found at elevations above 4500 ft., and the temperate deciduous forest formation found at lower elevations. Within each formation the forest may be further divided into recognizable associations of species that form distinct forest types. The forest types of the Southern Appalachians were identified and described by Braun (1950) in relation to the vegetation

patterns of eastern North America. She noted the Southern Appalachian forests to be outstanding, in terms of both the wealth of species and the mature size of the forest trees. The forest types of the Great Smoky Mountains National Park were analyzed in relationship to environmental gradients by Whittaker (1956) who recognized that they included some of "the most beautiful deciduous forests in the world."

Included within the variety of deciduous forest types found in the region are the cove forests, considered to be among the most unique features of the Southern Appalachians (Jackson, 1989). The cove forests have been labeled with a variety of names by different authors including Chestnut cove forest (Holmes, 1911), cove hardwood forest (Cain, 1943), and mixed mesophytic forest (Braun, 1950). Regardless of the name applied, each author has described essentially the same forest type.

The cove hardwood forests are characterized by a canopy of very tall trees (100-200 ft.) consisting of several deciduous species that share dominance including silverbell (*Halesia monticola*), basswood (*Tilia heterophylla*), sweet buckeye (*Aesculus octandra*), sugar maple (*Acer sacharum*), yellow birch (*Betula allegheniensis*), tulip poplar (*Liriodendron tulipifera*), and one coniferous species -- hemlock (*Tsuga canadensis*). The relative proportions of the individual species vary locally, but in combination these species comprise 80% to 90% of the canopy cover, with no one

species accounting for more than 25% to 30% of the canopy cover. In some cove forest stands, American chestnut (*Castanea dentata*) was previously an important canopy tree (Whittaker, 1956), but here and elsewhere in the eastern U.S. the species was eliminated by the chestnut blight (*Endothia parasitica*) that was accidentally introduced from Asia (Ogburn, 1975).

In many cove forest stands, a secondary canopy of smaller shade-tolerant trees and shrubs is found below the primary canopy. This secondary canopy may be composed of a variety of tree species, but is generally not as dense as the primary canopy. However, in areas where hemlock comprises a significant proportion of the canopy, dense thickets of rhododendron (*Rhododendron maximum*) may be found.

Ferns, mosses and shade-tolerant herbs carpet the ground during the growing season in nearly all stands, forming a dense and luxuriant understory that is among the richest found in the region (Cain, 1943). Only under hemlock and rhododendron is this understory typically missing or depleted. Apparently many of the understory plant species begin growth before either of the overlying deciduous canopies leaf out in the spring. Since hemlock and rhododendron are both evergreen, the perpetual shade in all seasons found beneath them renders the ground unsuitable for many understory herbs. Both of these evergreen species also deposit abundant amounts of highly acidic detritus that lowers the Ph of the soil, a

process that may also contribute to the paucity of the herb layer.

The cove forests of the Southern Appalachian region, while exhibiting a considerable degree of local variation, nonetheless represent a distinctive forest type of the temperate deciduous forest formation. Its essential characteristics include a dense canopy of a diverse assembly of very tall trees, a less dense secondary canopy of smaller trees and shrubs, and a shade-tolerant understory of herbaceous plants (Plate 1)¹. Considered as a whole, this forest type displays an unusually high degree of biodiversity for an extra-tropical environment.

2.3 Primeval Forests

A discussion of the forest conditions from the early historical period up until contemporary times presents a serious problem of semantics in that a variety of adjectives, with a variety of connotations, have been applied to describe the original condition or state of the forests.

Traditionally, any forest that had been unused by Americans of European descent was considered to be "virgin" or untouched. This description is inappropriate, since it ignores the impact of Native Americans on forests. It also downplays the role of natural disturbances such as fire,

¹ All Plates are in Appendix A.

flood, or windthrow, that significantly alter forest conditions and dynamics.

More recently, the term old-growth has been used widely to describe forests that are believed to have not yet been "touched" or exploited by humans, and that have not been severely affected by natural disturbances for some threshold time period, usually two-hundred years or more (Hunter, 1989). As a term of classification, "old-growth" is problematical, also. First, how old is old-growth and how many trees must be old for a forest to be old-growth? Different authorities have used different threshold values for both of these measures. Second, old-growth forests are not immune to natural disturbances, so not all the original forests would have been in an old-growth condition at any one time.

I prefer to use the term primeval to describe the original forest conditions that were encountered by European explorers and settlers. A primeval forest condition does not necessarily exclude disturbances, either human or natural, nor does it require a certain number of trees of a certain age class. Used here, the primeval forest condition is that state of the forest as it was at its earliest age for which one has a reliable knowledge or description of its character. It is therefore not limited to a singular state for the region as a whole, but rather it varies spatially as an expression of the balance of dynamic forces that vary temporally over localized

areas. These dynamic forces may include both natural processes as well as prehistoric human activity.

William Bartram, during his 1773 expedition to the Cherokee country (which approximately corresponds to the Southern Appalachian region) noted that the primeval forest condition was characterized by "magnificent high forests" (Bartram in Harper, 1958 p.213). However, from other descriptions of the landscape from this same expedition it is clear that some areas had been cleared and burned in proximity to the Cherokee settlements. The Cherokee settlements were distributed along the larger river valleys and basins of the region (Goodwin, 1977). Holmes (1911) noted that the forest vegetation of these larger basins was actually more closely allied to the adjoining piedmont area than to the rest of the region. Pine, which is associated with both human-set and natural fires, comprised between one third to one half of the forest stands in these areas. Clearly, the primeval forest condition included early successional landscapes that were at least partly a result of human-induced disturbances.

The primeval forests in other areas of the region appear to have been free of significant human disturbances. In the cove forest communities of the Joyce Kilmer Memorial Forest (JKMF) in Nantahala National Forest no evidence of fire, either human-set or natural, has been found (Lorimar, 1980). The JKMF stands consist of uneven aged trees that maintain shade-intolerant early successional species such as tulip

poplar (*Liriodendron tulipifera*) through windthrow disturbances that occur at fairly long, but irregular intervals (Lorimar, 1980). Based on the age of the oldest tulip poplars (approximately 500 years) within the uneven aged stand of the JKMF (Plate 2), it is unlikely that the area could have been an Indian old-field within at least the last half millennium.

That windthrow was a major natural disturbance of the primeval forests is corroborated by early historical records. In 1875 a storm in the upper valley of Thunderhead Prong in the Great Smoky mountains knocked down such a large group of giant poplars, that the area was named the "Blowdown" by the local inhabitants (Weals, 1991).

Canopy gaps (Plate 3) formed by windthrow disturbance events were an important factor contributing to the persistence of a shade-intolerant species such as tulip poplar within the canopy of the primeval cove forests. The ability of tulip poplar to establish quickly in gaps, combined with rapid height growth that permits it to overtop its competitors, allows it to function as emergents. The dynamics of the mesic forests of eastern North America have been recognized as being similar to the dynamics of tropical rainforests in certain ways, including the ability of shade-intolerant species to act as emergents (Sauer, 1988). In this sense, tulip poplar is one of the species that contributes to the similarity between the dynamics of eastern mesic forests

and tropical rainforests. Nonetheless, it typically comprised only a small percentage of the mature canopy trees in the cove forests. Apparently, even in gap stands that begin with large numbers of tulip poplar sprouts, chestnut (*Castanea dentata*) could often outgrow the tulip poplar during the first 80 years, and effectively suppress the number of tulip poplars that reached maturity (Ayres and Ashe, 1905).

Fire was not a normal disturbance of the primeval cove forests. The topographic setting of the cove forests -- in coves and lower slopes, especially with north and east exposures -- has very favorable moisture conditions. Even during the early part of this century when people commonly set fires, Holmes (1911) noted that they were much less frequent in the cove forests because of the moisture.

Research within the Great Smoky Mountains National Park revealed that today natural and human-set fires have distinctively different spatial distributions. Natural fires occur along the ridges and the drier southern and western slopes, while anthropogenic fires are most common in proximity to roads at low elevations (Harmon, 1981).

The primeval forest conditions of the Southern Appalachian forest region varied spatially, with the larger valleys and basins characterized by open areas and early successional forest stands with a high percentage of various species of pine that were not unlike the forests of the Piedmont region. The primeval forest condition within these

areas was at least partially related to human activity.

In the more rugged mountainous areas, forest cover was more continuous. Open areas or early successional forest communities may have been present, but would have been limited to topographic situations where restricted soil moisture would allow natural fires to develop on a fairly regular basis. Ridges, steep slopes, areas of shallow soils, and slopes with southern or western aspects would be fire-prone topographic situations. The forest communities in these areas were dominated by chestnut and various species of oak. Pine was also present in some stands but only where several topographic factors combined to severely restrict soil moisture.

In the rugged mountainous areas, coves, narrow valleys on gently sloped areas, and slopes with northern and eastern aspects had a primeval forest condition consisting of an almost continuous forest canopy, with only small and isolated gaps created by windthrow events. The limited spatial extent and relatively long recurrence interval of windthrow events for any one location, in combination with the favorable moisture conditions in these topographic settings, favored the growth of very large and long-lived trees. Both cove forests and chestnut forests were found in these areas.

2.4 The Primeval Cove Forests

Although one can not be altogether certain that Bartram was describing a primeval cove forest when he commented on

"the stately columns of the superb forest trees..." (Bartram in Harper, 1958, p. 216) in the vicinity of what is today Clayton, Georgia, his later comments on "a very extensive forest, consisting of the Hemlock spruce (*P. abies*) [sic] almost encircled by distant ridges of lofty hills." (Bartram in Harper, 1958, p. 230) near Januluska Creek in western Macon County, North Carolina clearly describe a hemlock bottom within a cove forest. In detailing his travels throughout the Cherokee country of the Southern Appalachian region during the spring of 1773, Bartram commented about the forests being "lofty" (p. 211), "extremely well timbered", (p. 212) "incomparable" (p. 213), and "sublimely high" (p. 217). While traveling in the vicinity of modern-day Franklin, North Carolina, one of the open areas in the broad valley basin of the Little Tennessee river, the "now spacious and well beaten" path took him "mostly through fields and plantations...of Corn, Beans, &c..." (Bartram in Harper, 1958 p. 221)

Accounts of other early explorers and settlers describe the original forest as "wonderful in the extent, density, size, and quality of its timber trees, ..." (Ayres and Ashe, 1905) and of containing "avenues of tulip like the big trees of California" (Braun, 1950). Randolph Shotwell described some forest stands in western North Carolina as "lofty and vigorous beyond anything I have seen..." (Van Noppen and Van Noppen 1973). Some of the early descriptions included actual measurements such as one from 1859 in which an

individual tulip poplar eleven feet in diameter was recorded (Buckley in Stupka, 1964). There are other accounts of walnut trees eight feet in diameter and wild cherry trees up to four feet in diameter (Van Noppen and Van Noppen, 1973). In 1848, while exploring the Nantahala mountains, Charles Lanham wrote, "among the forest trees were many chestnut and poplar specimens, which were at least seven or eight feet in diameter" (Ogburn, 1975).

The historical logging record, including old photographs, also gives testimony to the truly magnificent size of the primeval cove forest trees. Cases have been recorded of an individual tulip poplar tree containing up to 20,000 board feet of merchantable timber (Murlless and Stallings, 1973) and a single acre in the Smoky Mountains yielding 100,000 board feet of timber (Weals, 1991).

Photographic evidence of the incredible trees of the primeval cove forests include photographs of the trees themselves as well as the giant logs into which they were cut. Photographs of the trees themselves include one of a chestnut located below Tremont Falls that appears to be at least five feet in diameter judging from the children standing in front of it. Still others show tulip poplars that are up to seven feet in diameter. Photographs of logs six feet in diameter are common. Some logs were so large that only a few would fill a wagon or railcar, and in at least one photograph a log was so large that it filled the bed of a logging truck

completely.

2.5 Human Impacts

The primeval forests in general, and the primeval cove forests in particular, have been greatly impacted since the arrival of European settlers. The earliest settlers cleared some forest for agricultural use, but this was mostly restricted to the larger valley and cove sites, some of which had previously been occupied by Native Americans.

Logging operations had a significant impact on forest conditions throughout the region. The earliest logging consisted of harvesting trees to meet the local needs of subsistence farmers. Prior to the Civil War, limited commercial logging operations were selectively harvesting the finest specimens of the most valuable hardwoods such as ash, cherry, and walnut from sites close to major streams. Only these most valuable trees in the most accessible areas could economically be transported to markets outside the mountains (Lambert, 1961). This early logging period resulted in the perimeter forests being essentially culled of many of the largest trees.

In the Little River watershed in Tennessee, the first phase of commercial logging began in the 1880s. These logging operations consisted of widespread harvesting of trees (especially tulip poplar) in areas close to existing wagon roads. In general, the sawmills were located outside the

immediate region, so harvesting of trees was limited to areas that had transportation readily available. Later, from 1896 to 1900, splash dams were constructed to use the rivers to transport the logs to sawmills downstream (Burns, 1952). Although the total volume of lumber harvested by these early commercial operations is not known, the combined effect of these operations and the earlier harvesting by subsistence farmers was a significantly reduced volume of standing timber in the perimeter forests. By 1900, selective harvesting of the best trees and the complete harvesting of easily accessible stands had been practiced for at least 70 years within the Little River watershed.

Ayres and Ashe (1905) examined forest resources in the area during 1900 and 1901, by traveling along roads and trails. They used "ocular estimates... checked occasionally by actual measurements on small representative areas" to estimate timber volume. According to their estimates 288,000,000 board feet of timber was available in this basin. However, estimates based on sawmill production records for the Little River Lumber Company, which began harvesting timber in 1903, indicate 560,000,000 board feet of timber were produced from this basin by the time operations ceased in 1938 (Lambert, 1961). Apparently, Ayres and Ashe were off by nearly 100 percent in their estimates! (Table 2.1). The discrepancy probably arose from their estimating the standing timber of the perimeter forests. The perimeter forests had

already yielded significant amounts of timber during the preceding 70 years. The sample they used was not truly representative of the whole forest. Thus when Ayres and Ashe extrapolated their results to the whole basin, they underestimated the actual volume of timber that was still standing in the Little River basin.

Historical records from other areas of the region confirm the pattern of the first phase of forest resource exploitation illustrated by the example of the Little River Basin. In

TABLE 2.1
Comparison of Little River Timber Records

Source	Ayres & Ashe	Lambert	
Time Period	1900-1901	1903-1939	1830-1939
Timber Yield (1000s Bd.Ft.)	288508	560000	1000000
Forested Acres ¹	61485	61485	64755
Yield/Acre (Bd.Ft.)	4692	9108	15443
Hemlock (Percent)	11.2	23.6	NA
Tulip Poplar (Percent)	1.4	10.7	NA

Sources:

Ayres and Ashe 1905. *The Southern Appalachian Forests*
USGS Professional Paper No. 37, U.S. Government
Printing Office, Washington, DC.

Lambert, Robert S. 1961. "Logging on Little River, 1890-
1940," *The East Tennessee Historical Society's*
Publications, No. 33.

¹All acreage statistics based on Ayres and Ashe data.

western North Carolina early settlers were all lumbermen to an extent, harvesting trees to meet local demand for lumber. Commercial logging first used rivers as a natural means of transport. In one instance, splash dams were constructed to move logs down the Catawba river all the way to a sawmill in Hickory, North Carolina (Van Noppen and Van Noppen, 1973). Based on the pattern of timbering before 1900, it is very probable that Ayres and Ashe underestimated the timber resources in the whole region and not just the Little River basin.

The second phase of commercial logging began around 1900, in both North Carolina and Tennessee, when railroad lines were extended into previously inaccessible areas. Wholesale harvesting of trees by capital-intensive firms proceeded at a rapid pace and was fueled by national demand for timber. Hardwood supplies had already been exhausted in some of the northern states, and lumbermen and investors from outside the Southern Appalachian region realized that the timber resources of the region could meet the demand if the timber was transported by rail (Lambert, 1961; Van Noppen and Van Noppen, 1973).

In addition to the obvious impact of the actual timber cutting, these operations affected the fire regime of the Southern Appalachian forests. The loggers took the merchantable boles, but left huge amounts of unmerchantable slash and logging residues that contributed to the fuel load.

If the increased fuel load was not ignited by natural causes, the loggers' careless use of kerosene, woodfires, or the cinders from their coal-fired steam engines would often set fires (Weals, 1991). Such fires were probably often more intense than earlier fires had been, owing to the greater fuel load. Thus, the increased intensity and frequency of fires was an additional secondary impact on the Southern Appalachian forests.

The accidental introduction of the chestnut blight shortly after the turn of the century seriously impacted both the chestnut forests and the cove forests of the region. By 1910, trees in North Carolina were infected, and by 1940 nearly all mature chestnut trees in the region were dead (Ogburn, 1975). Although surviving rootstocks continue to send up new stems, these chestnut sprouts are invariably killed by the blight before they reach reproductive age or canopy height. While the elimination of chestnut from the forest canopy was favorable for its forest competitors, it was very unfavorable for animal wildlife. Chestnut, unlike oak, was a consistently reliable producer of mast. The loss of chestnut has greatly reduced the carrying capacity of the forest especially during years when the oaks have low mast production (Houk, 1993).

Human impacts on the Southern Appalachian forests during the past few centuries have dramatically altered the condition of the forests. As a result, few contemporary forests mimic

the primeval forest conditions. Clearcuts and fires have disturbed large areas, including areas of cove forest. Even within the confines of the Great Smoky Mountains National Park, it has been estimated that 80 percent of the forest area has been significantly disturbed by humans (Houk, 1993). The clearcuts and fires, which leave large sunny openings, have favored tulip poplar over other species in the cove forests. The absence of competing chestnut trees allows many more of the tulip poplar seedlings to survive. This process results in secondary cove forests with much higher percentages of tulip poplar than existed under primeval conditions, where reproduction was limited to spatially restricted windthrow clearings.

2.6 Biodiversity

The Southern Appalachian region is a center of biological diversity within the temperate zone of the western hemisphere (Whittaker, 1973). For example, in the Smoky Mountains of this region, salamanders achieve their greatest diversity outside the tropics, with five of the nine salamander families represented (Houk, 1993). While the biota includes an abundant array of both plant and animal species, the region is most noted for the diversity of its flora. The climatic history of the region is at least partially responsible for the diverse assembly of plant species that has developed. Unlike Europe and Asia, where the dominant mountain systems

have an east-west orientation, the mountain systems of North America are oriented north-south. In the case of Eastern North America, many boreal species were able to migrate southward during glacial periods, unimpeded by topographic barriers. When the climate warmed, the species migrated northward, and also moved upward, establishing refugia in the high elevations of the southern Appalachians. Warm temperate zone species also migrated southward during glacial advances. These warm temperate species survived glacial periods in protected refugia along the bluffs of the lower Mississippi River valley and in sheltered locations within the Southern Appalachians, and migrated northwards from these sites as the climate warmed (Delcourt and Delcourt 1984). The mixing that resulted from the migration of species in response to climatic changes of the Pleistocene left the Southern Appalachians with a native flora that includes species with both boreal and warm temperate (subtropical) affinities.

The relatively high relief and rugged terrain of the region has also contributed significantly to the diversity of the native flora. Significant local variations in slope, aspect, and elevation result in contrasting conditions of moisture, insolation and temperature that have a controlling effect on the physiological processes of plants, and ultimately the suitability of a site for a particular plant species.

While the native flora contains both woody and herbaceous

species, the patterns of biodiversity of these two plant forms are inversely related, i. e., the peak diversity of woody species is found at low elevations, while the herbaceous species achieve their peak diversity at high elevations. Overall, the greatest diversity of woody species is found in the cove hardwood forests, and the greatest diversity of all plant species is found in the transition from the cove hardwood forests to mesic slope forests (Whittaker, 1956). A quarter acre of cove forest has up to six times as many species of vascular plants as does the same area of spruce-fir forest (Houk, 1993). Thus, as a single forest type, the cove hardwoods contribute most significantly to the overall biodiversity of the region, despite the fact that they account for only one third of the forested area (Frothingham and Stuart, 1926). However, not all cove hardwood forests are of equal richness. The cove forests in the Black Mountains of North Carolina were not as rich as the cove forests in the Great Smoky Mountains. The coves of the Black Mountains contained communities typical of dry slopes (Braun, 1950).

2.7 Conservation

While the forests of the Southern Appalachians have been severely impacted by human activity during the settlement and subsequent development of the region, conservation efforts have been extended to minimize continued abusive impacts. Most of these efforts have only been initiated within the last

75 to 80 years. Notable examples of conservation efforts include the Weeks law of 1911, which established National Forests in the region; the establishment of the Great Smoky Mountains National Park in 1938; and more recently, the designation of wilderness and wildlife management areas such as the Joyce Kilmer Slickrock Wilderness and the Southern Nantahala Wilderness (Van Noppen and Van Noppen, 1973).

Recently, it has been suggested that conservation efforts should shift focus from trying to preserve individual species, and instead focus on the preservation of the larger ecosystem that provides the ecological niches that endangered and threatened species require to survive. If conservation policies directly insure the survival of the ecosystem as a whole, they will indirectly insure the survival of the more vulnerable species (Haney in Stevens, 1993). Accepting the wisdom of this policy direction suggests that in the case of the Southern Appalachian region, conservation of the ecosystem responsible for producing cove forests of primeval conditions should be a priority. Implicit in such a policy is the understanding that an ecosystem transcends the boundaries of individual forest preserves. Therefore, to maintain a functioning ecosystem that conserves cove forests that at least approximate primeval conditions, the ecosystem must be analyzed from a regional viewpoint.

Even the most cursory glance of the environmental conditions in the Southern Appalachians suggest that the

exceptional quality of the primeval cove forests may be related to the exceptionally high rainfall that many portions of the region receive. Considered with the exceptional biodiversity, the primeval cove forests of the region display characteristics usually associated with temperate rainforest environments. Primeval cove forest conditions may actually represent the product of a temperate rainforest ecosystem. The identification of the temperate rainforest environments would be an essential first step in implementing a regional conservation policy that seeks to preserve the underlying ecosystem as a whole, in order to preserve individual species as a part.

CHAPTER 3

TEMPERATE RAINFOREST VEGETATION AND CLIMATES

3.1 Rainforests

The term rainforest was originally coined by the German plant geographer A.F.W. Schimper in 1898 to describe the climatic climax vegetation formation typically found within the equatorial zones of the earth, where consistent heat, light and abundant moisture promoted vigorous vegetative growth year round (Silverberg, 1967). In essence, the rainforest is an environment where the photosynthetic process, by which green plants use visible light to manufacture carbohydrates, can proceed unimpeded because the prerequisite inputs, most especially water, are never seriously limited by climatic factors.

The term includes two distinct components. The first (rain) involves a type of climate, by definition one with exceptionally heavy annual rainfall. The second (forest) involves a type of vegetation formation, by definition a luxuriant forest of lofty trees forming a continuous canopy. While the term rainforest was originally applied to both tropical and temperate forest formations (Schimper, 1903), in modern English it generally refers only to tropical forests. This modern usage seems to stem from the fact that in comparison to temperate rainforests, tropical rainforests cover a much greater land area and have been the subject of

more intense scientific research. As a consequence of the greater scientific attention received by tropical rainforests, these forests have been more precisely defined in relation to both climatic characteristics and vegetation characteristics.

3.2 Tropical Rainforest Formation

To clarify the character of temperate rainforest formations, it is essential to briefly examine the better studied and more clearly defined character of tropical rainforests. Obviously, tropical rainforests occur within the tropics, and generally at low to moderate elevations, where warm temperatures prevail.

The tropical rainforest forms a continuous canopy, but of irregular height since it is composed of several distinct layers. The tallest trees are widely spaced and often form broad crowns that emerge above the general level of the canopy. These trees are referred to as emergents. When viewed from above, the canopy of the rainforest not only varies in terms of its height, but also in color owing to the great variety of tree species present. Below the upper canopy, a second layer of trees often forms a closed cover of interlocking crowns. A third layer of still lower trees with more narrow crowns may be found below this second layer (Money, 1978).

While the environment of the tropical rainforest favors vegetative growth, extreme competition for light greatly

influences the adaptations of the plant forms. Within the various canopies, epiphytes and lianas (woody vines) are common. The ground surface beneath the rainforest is relatively open, since the multiple canopy layers filter out most sunlight. Few green plants can survive in the deep shade at ground level. Sometimes heterotrophic plants are found at this level (Richards, 1971).

Occasional disturbances create openings in the canopy that are rapidly colonized by a myriad of species (Schimper, 1903). Climate-related disturbances include windthrow, flooding and fire. Windthrow events are probably the most common climate-related natural disturbance type, with fires occurring mainly as a result of human activity. Flooding may be more important locally in proximity to watercourses. Thus the distinguishing features of tropical rainforest vegetation formations include:

1. a multiple-canopied forest of evergreen trees
2. an emergent class of very tall trees
3. a profusion of lianas and epiphytes
4. occasional gaps created by windthrow events
5. among plants, an intense competition for sunlight
6. high biodiversity

This last named feature, biodiversity, refers to the great variety of both plants and animals that is a hallmark of tropical rainforest. Tropical vegetation of superlative

richness, luxuriance, and abundance is implied anytime the more generic term rainforest is used in English. But these characteristics are also found in the rainforest vegetation of the temperate regions.

3.3 Temperate Rainforest Vegetation

The term temperate rainforest has been used by plant geographers and ecologists to describe a number of apparently disparate forest formations. Schimper (1903) considered the essential identifying characteristic of the temperate rainforest formation to be the canopy of broad-leaved evergreen trees. He regarded temperate rainforests, which he identified in southern Japan and northern New Zealand, to be impoverished forms of tropical rainforest. He noted that deciduous trees were often a subordinate within this formation, but became increasingly important toward the poleward margins of this formation.

Schmithüsen identified a temperate broad-leaved evergreen rainforest in Chile that included some needleleaf conifers (Veblen et al., 1983). This classification differs from that presented by Oberdorfer, whose Chilean rainforest formation encompasses a deciduous forest subtype within the temperate rainforest class (Veblen et al., 1983).

Campbell (1926) provided detailed descriptions of the vegetation in the temperate rainforests of Japan. In the southernmost areas these temperate rainforests are composed of

broad-leaved evergreen forests that exhibit strong tropical affinities, including an abundance of *Camellia* and other members of the tea family (*Theaceae*). Farther north the broadleaved evergreens grade into a mixture of conifers and broadleaved deciduous trees. Eventually at the poleward margins, the deciduous trees predominate.

In New Zealand, the unifying characteristic of all formations identified as temperate rainforest is the distinct development of multiple canopy layers in response to competition for sunlight. The tallest trees form a discontinuous layer, with a more continuous secondary tree layer below. The third layer is composed of larger shrubs and tree ferns, and below this layer at ground level is a dense understory of small ferns (Cockayne, 1971).

According to de Laubenfels (1975), temperate rainforest vegetation contrasts sharply with adjacent forest formations, with the development and density of the understory being the best indicator of a rainforest formation. The canopy mitigates adverse environmental conditions such as extremes of dryness and cold that would otherwise damage the vegetation of the understory. In some instances, heavy rainfall can also compensate for lower minimum temperatures in cold winter areas.

The observed variety of forest types that fall within the temperate rainforest concept makes it nearly impossible to distill one element that uniquely establishes the character of

these different forests (Money, 1978). Nonetheless, their character can be established by considering a combination of common traits. The variation of temperate rainforest formations among world regions can be better understood as an expression of several temperate rainforest subtypes produced by differing climatic regimes.

3.4 Temperate Rainforest Traits

The most common trait is the prevalence of trees with exceptionally large trunk diameters and equally impressive heights, easily in excess of 100 ft. and occasionally even exceeding 200 ft. In undisturbed locations individual trees achieve the largest size, in terms of height and girth, for their respective species. The trees are also long-lived, with ages often measured in centuries rather than decades. In general the oldest specimens for a representative species will be found within temperate rainforests. Examples include the Kauri (*Agathis*) of New Zealand, the giant conifer (*Fitzroya cupressoides*) of Chile, the giant Cedars (*Cryptomeria*) of Japan, the Redwoods (*Sequoia*) of California, and the Sitka Spruce (*Picea*), Douglas Fir (*Pseudotsuga*) and Hemlock (*Tsuga*) of the Olympic Peninsula of Washington.

The prevalence of nurse logs, colonnades, and stilted trees are an interrelated trait that distinguishes temperate rainforests. Old or dead trees collapse forming logs that initiate this process. Owing to the extremely moist

environment, the log begins to decay, and tree seeds actually sprout upon the log. The log itself becomes a tree nursery, hence the term nurselog (Plate 4). Not all of the tree seedlings that sprout on a nurselog will survive to maturity. However, if several survive, they will all have a distinctly linear arrangement, being oriented along the axis of the nurselog. This type of arrangement is referred to as a colonnade (Kirk, 1966). Finally, after many years the nurselog will completely decompose, leaving the now-mature seedling trees resting on stilted roots that originally wrapped themselves around the nurselog (Plate 5).

In addition to the canopy of tall dominant trees, temperate rainforests are composed of other canopy layers, including a secondary tree layer that often has lianas and epiphytes present, but to a much lesser extent than in the tropical rainforests. A notable exception is found in the Olympic peninsula rainforest, where the abundance of epiphytes is comparable to tropical rainforests (Nadkarni, 1985). This secondary canopy includes shade-tolerant species and may also include immature trees of the dominant class.

In contrast to the tropical rainforests, temperate rainforests exhibit dense undergrowth that almost completely covers the ground. In areas not covered by growing vegetation, the ground is covered with a dense layer of organic matter. This dense undergrowth includes an abundant array of herbaceous plants, mosses, lichens and ferns. This

contrast may be related to the lower rates of decay under temperate conditions. In temperate rainforests the soil is covered with a nutrient rich layer of organic matter that may favor the development of the dense undergrowth. The wide variation in solar angles and photo periods may also result in increased light penetration of the canopy cover.

Finally, the trees species can be predominantly evergreen, either broadleaved with tropical affinities, or needleleaved with boreal affinities, or deciduous broadleaved with typically temperate affinities. Most often the trees will include a mixture of at least two of these three types. This mixture of tree species with differing affinities, combined with the lianas and epiphytes of the secondary layer, and the dense undergrowth of the ground layer together contribute to the most distinctive trait of a the temperate rainforest -- a level of biodiversity that is unmatched outside of the tropics.

In summary, the temperate rainforest traits that effectively distinguish these forests from ordinary forests include:

1. Large trees (girth, height, and age) for the respective species.
2. Nurse logs, colonnades, and stilted trees.
3. Multiple canopies, that include lianas and epiphytes.
4. Dense undergrowth of mosses, lichens, and ferns
5. Exceptional degree of biodiversity outside of the

tropics

In addition to these vegetation traits, the temperate rainforest formation has another trait related to topography. Their best development occurs locally on moderate slopes and in valleys where soils are relatively deep. Only in these localized sites will one find all the distinguishing traits fully developed in proximity to each other.

3.5 Temperate Rainforest Climates

Climate influences the extreme variety of temperate rainforest formations. There is no singular temperate rainforest climate, but rather a series of climates, each with a distinctive regime of seasonal temperature and moisture conditions, that supports a distinctive rainforest formation. Despite differences in the seasonal climatic regimes, all temperate rainforest formations are found in temperate regions with high annual rainfall, even if dry conditions prevail for part of the year. Excessive rainfall within the temperate zones cannot occur regularly without orographic uplift of airmasses to enhance the precipitation process. Thus, temperate rainforest climates are always associated with mountainous regions.

The temperate rainforest vegetation can be better understood as the expression of four distinct temperate rainforest climate types, arranged geographically into two classes, namely the west coast rainforest climates and the

east coast rainforest climates (Table 3.1).

3.6 Western Temperate Rainforest Climates

On the western margins of the continents between approximately 42° and 55° latitude, wherever mountains interrupt the flow of the cyclonic westerly storm systems, the precipitation process is enhanced resulting in prodigious amounts of rainfall. This process results in the development of the cool temperate rainforest climate. The cool rainforest climate supports evergreen vegetation that has closer affinities with the boreal forests than with tropical rainforests, since conifers are the dominant tree type.

The influence of maritime airmasses results in moderate temperatures at all seasons, with pronounced extremes of heat or cold occurring only at infrequent intervals. While the growing season is very long, growth proceeds at a much slower rate since temperatures are relatively low. The precipitation regime has a definite winter concentration of rainfall but no significant summer drought.

In mountainous regions equatorward from this first western rainforest climate, from approximately 35° to 42° latitude, the summer-dry rainforest climate prevails. This climate includes heavy rainfall in the winter half of the year, but is marked by a significant summer drought. The annual totals of precipitation are still large, but the dry conditions during the summer reduce the overall growth of

TABLE 3.1

Comparison of Rainforest Types

Type	Approximate Latitudes	Growth Limiting Factor	Typical Dominant Vegetation
<u>Tropics:</u>			
Tropical	0°-15°	NA	Broadleaved Evergreens
Monsoon	15°-23°	Drought	Broadleaved Deciduous

<u>Temperate Western Coasts:</u>			
Summer-Dry	35°-42°	Drought	Mixed Needleleaved & Broadleaved Evergreens
Cool Temperate	42°-55°	NA	Needleleaved Evergreens

<u>Temperate Eastern Coasts:</u>			
Warm Temperate	23°-33°	NA	Broadleaved Evergreens
Summer-Green	33°-38°	Cold	Broadleaved Deciduous

vegetation. In some cases, fog and mist from marine airmasses contribute moisture that moderates the summer drought. Compared to the first west coast rainforest climate, the temperatures are generally warmer owing to the lower latitudes, but are still relatively moderate because of the influence of marine airmasses.

This summer-dry rainforest climate supports vegetation that includes both evergreen conifers and broadleaved evergreen trees. The summer drought conditions favor fire as a disturbance type and increase the importance of topographic control on the development of the rainforest.

3.7 Eastern Temperate Rainforest Climates

In mountainous regions on the eastern coasts of continents between approximately 23° and 33° latitude, a warm temperate rainforest climate supports vegetation most closely resembling that of the tropical rainforest. The subtropical temperature regime and heavy rainfall of the eastern temperate rainforest climate supports plant growth in all seasons, but the noticeably cooler and often drier winter season reduces the overall productivity of the vegetation in comparison to tropical rainforests. Broadleaved evergreen trees typically dominate, with abundant lianas and epiphytes present. The native flora of these climates usually has a strong tropical affinity. While this *climate* is widespread in Asia, from the Himalayas in the west, to southeastern China, Korea, and Japan

in the east, a long history of human occupation has virtually eliminated the original rainforest vegetation.

In the southern hemisphere, limited areas in the southeastern parts of Brazil, South Africa, and Australia also are included in this class. The northern portion of the North Island of New Zealand, although technically outside of the latitudinal parameters previously mentioned, could be considered within this class.

Schimper (1903) included parts of the southeastern United States within this class based on the tropical affinities and evergreen vegetation. I do not believe this climate is wet enough to develop a true warm temperate rainforest formation, although the natural vegetation has clear tropical affinities.

Poleward of this first east coast temperate rainforest climate, from approximately 33° to 38° latitude, a summer-green temperate rainforest climate with a pronounced cold season prevails. However, the abundant moisture during the long growing season permits rapid vegetative growth that compensates for lack of growth during the dormant season. The vegetation in this type of climate is dominated by deciduous broadleaved trees, but needleleaved evergreens and to a much lesser extent broadleaved evergreens are also present.

Frost and even snow may occur in this climatic regime, but overall the winter season is relatively brief, and not particularly cold. All monthly mean temperatures normally average above 32° F (0° C.), with six to nine months averaging

above 50° F. (10° C.). During the height of the summer season conditions of temperature and humidity strongly resemble the regime of tropical rainforest climates (Ogburn, 1975), i.e., daytime maximum temperatures regularly reach the mid 80s F. (30° C.) with monthly dewpoint temperatures averaging between 60° and 70° F. (15°-21° C.).

This second type of Eastern rainforest climate is the type that is found within the Southern Appalachian region.

3.8 Quantitative Measures of Rainforest Conditions

The discussion of both temperate rainforest formations and climates up to this point has focused on qualitative descriptions. In the case of the temperate rainforest formation itself, I have distilled several key traits from the many qualitative descriptions in the literature. These traits have previously been listed. However, while these key traits are universally found in all the different undisturbed temperate rainforests, I cannot present any index or method to quantify these purely qualitative features. How many nurse logs must be present per unit area? How many epiphytes or ferns must be present? How rich and lush must the herbaceous understory be? Questions such as these are beyond the scope of this study. Kirk (1966) commented:

'With each forest the overall quality of growth is what says, "This is rain forest and that is not"-and "quality" remains ever beyond definition. Species and mechanisms are easy to describe- but how do you pinpoint the essence of rainforest, the Oriental *suchness*? How do you define beauty?'

Taken to heart, this commentary suggests that quantification of these key traits may ultimately be beyond any study. However, the traits may be used as a checklist. Noting the presence or absence of key traits within a given forest will be useful as a guideline to determine if a stand is a likely candidate for the rainforest designation.

Quantification of temperate rainforest climates is not quite as difficult. However, unlike tropical rainforests that share fairly uniform thermal conditions and can therefore be confidently assigned a single threshold quantity of rainfall to delimit their extent, the location of temperate rainforests across a wide range of latitudes (and thus temperature regimes), precludes the assignment of a single threshold value of annual rainfall that accurately defines their limits.

Thornthwaite (1931) presented a quantitative climatic classification system based on the calculated effectiveness, in terms of vegetative growth, of precipitation and temperature. This system provides an excellent method with which to quantitatively determine the limits of the temperate rainforest climates. Thornthwaite recognized five humidity provinces based on a comparison of Precipitation Efficiency (P-E) Indexes and characteristic vegetation for many stations (Haurwitz and Austin, 1944). Rainforest vegetation develops in areas with a P-E Index in excess of 128, which is classified as an A (wet or perhumid) climate. Five similar classes based on the Thermal efficiency ratio (T-E Index)

comprise the temperature provinces. This system recognizes that rainforests can develop in the tropical, mesothermal (warm-temperate), and microthermal (cool-temperate) provinces.

The calculated Precipitation Effectiveness Ratio is expressed by the formula:

$$115[(P)/T-10]^{10/9}$$

where P is mean monthly precipitation in inches, and T is mean monthly temperature in degrees Fahrenheit. The summation of the calculated monthly P-E ratios for all twelve months results in a number representing the P-E Index.

The formula for the Thermal Efficiency Ratio is:

$$(T-32)/4$$

where T is the mean monthly temperature in degrees Fahrenheit. The sum of the 12 monthly T-E Ratios comprise the T-E Index.

Using the Thornthwaite system, a temperate rainforest climate would have a P-E Index of 128 or higher, and a T-E Index between 32 and 128. This system has two distinct advantages. It relies on objective, standardized measurements that are widely available and can also be used to distinguish between warm temperate and cool temperate rainforests.

Temperate rainforests would be expected to be the most

productive forest sites outside the tropics. The combination of moderate temperatures and abundant rainfall provide ideal conditions for potential productivity and growth of trees. Paterson (1956) developed the climate vegetation productivity index (CVP Index) to predict potential productivity of forest sites all around the world. Since temperate rainforests should have a high potential productivity level, the CVP index may provide another means for determining the extent of temperate rainforests.

The equation for calculation of the CVP Index is:

$$\frac{(T_v * P * G * E)}{(T_a * 12 * 100)}$$

where T_v is the temperature of the warmest month in degrees Celsius, P is mean annual precipitation in millimeters, G is the growing season in months (mean temperature 3 degrees C or higher), E is the evapotranspiration factor, and T_a is the annual range in temperature (Degrees Celsius).

The CVP index offers a similar advantage to the Thornthwaite system, in that it uses readily available data. It does not, however, distinguish between thermal regimes.

CHAPTER 4

METHODS

4.1 GIS Database Design

The methods used to identify temperate rainforest environments in the Southern Appalachians involve two distinctly different scales, with each one requiring the development of a separate database. While the databases are developed separately, the results from the analysis of the local study area are later combined with the results from the regional climatic database to determine preliminary estimates of the extent of temperate rainforest environments for the whole region.

The regional GIS database includes climate data layers compiled from meteorological statistics (NOAA, 1988) for the respective states in the region. The local database includes a topographic data layer derived manually from USGS topographic maps, as well as land use and forest vegetation layers derived from the 1990 Landsat TM satellite image. The sources, processes, and output of the GIS data layers are summarized in Figure 4.1.

4.2 Climatic Database

I developed a regional climatic database for weather stations within the Southern Appalachian region. This

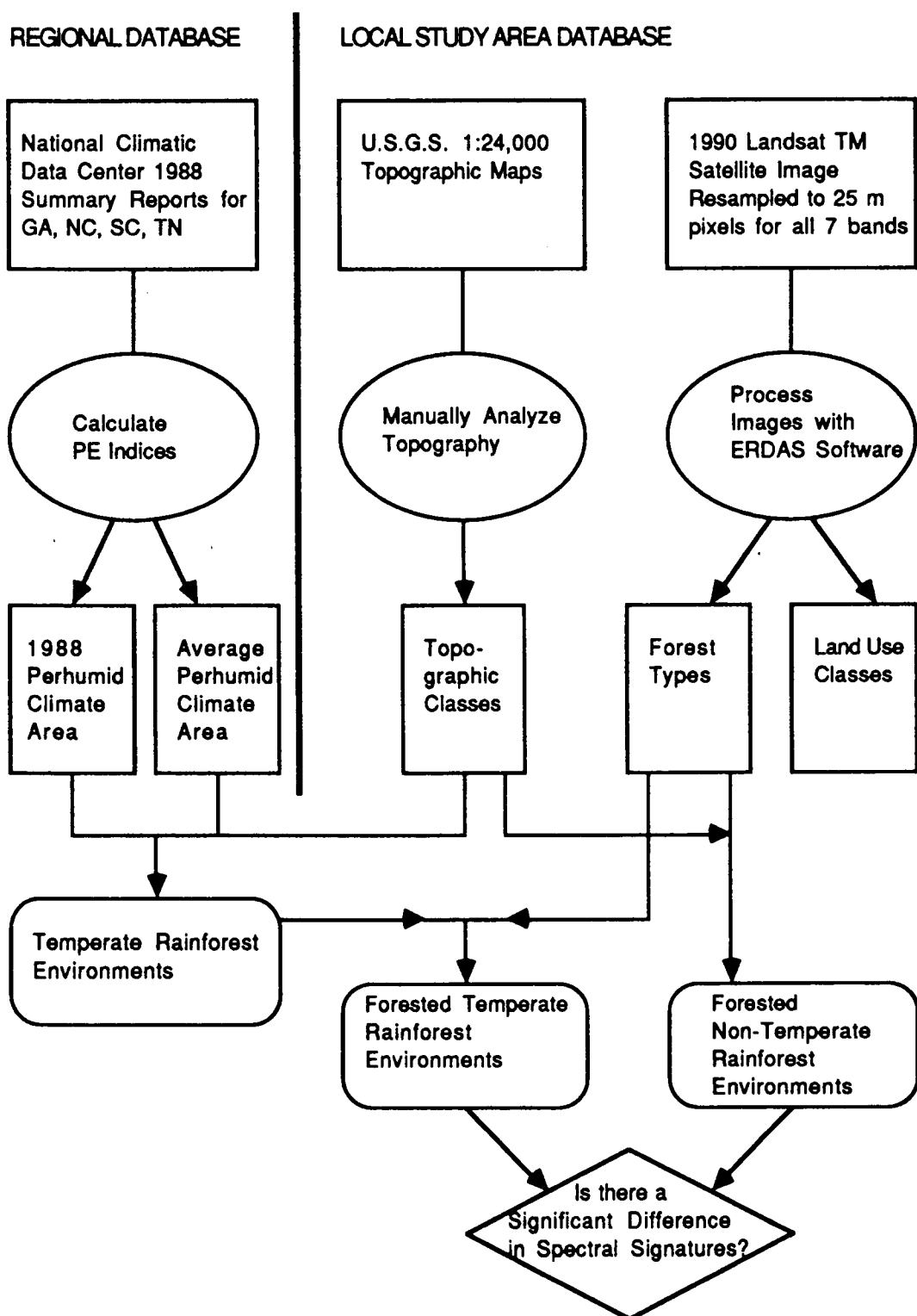


Figure 4.1 Database Design and Integration

regional database included both long-term averages of monthly precipitation and mean monthly temperatures (1951-1980) published by the National Climatic Data Center.

I used the Thornthwaite PE Index within the regional climatic database for two distinct reasons. It relies on two climatic variables, namely monthly precipitation and mean monthly temperature, that are widely available. In addition, the PE Index may also be used to estimate the relative probability of fire for individual drought years.

During the drought from 1986 to 1988, much of the southeastern United States was plagued by a combination of deficient rainfall and above normal temperatures. The Southern Appalachians were no exception. I selected monthly precipitation and mean monthly temperatures from 1988 to represent the region under conditions of extreme drought. Additionally, I obtained 1926 climatic data for two stations from the National Climatic Data Center Archives in Asheville, North Carolina. 1926 was the driest year of record in the Southern Appalachian region, and fires were extremely widespread. This limited 1926 data provides an important point of reference for calibrating the PE Index to fire potential.

Weather stations included in this database were not restricted to the high rainfall area, but rather, purposely included locations from the drier Piedmont and Valley and Ridge physiographic provinces. In all, 96 stations from

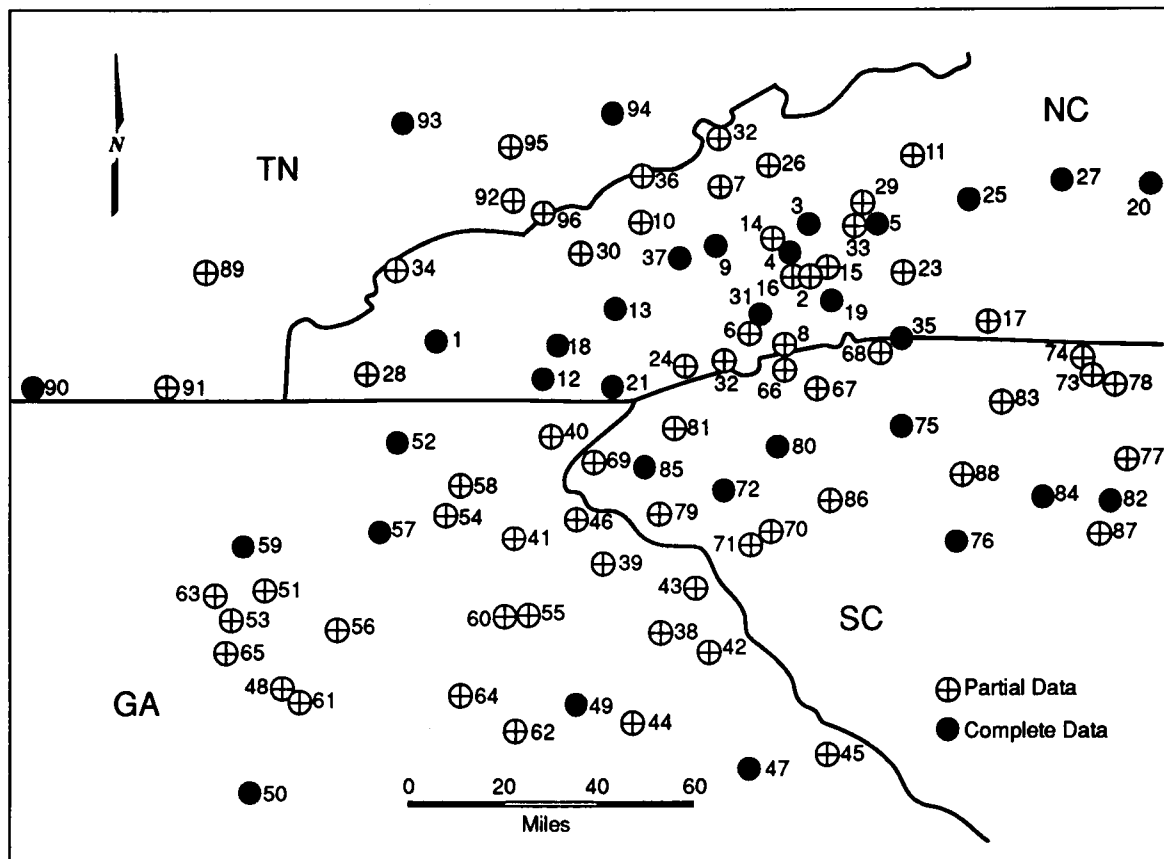
Georgia, North Carolina, South Carolina, and Tennessee were included in the database (Figure 4.2).

I included two elements in the final regional climatic database. The first element included the calculated PE Index under normal conditions. The second element included the calculated PE Index for representative drought conditions.

For the prerequisite temperature data, 28 stations lacked monthly mean temperature observations. Owing to the lack of observations, these stations also lacked mean monthly temperatures for the 30 year normal. Twenty-three additional stations lacked normal mean monthly temperature data because their temperature records were shorter than 30 years (the 30 year threshold is required to calculate a normal). I developed a model to systematically estimate the missing temperature values, so that all weather stations could be included within the database.

Ordinarily, I would have first used the standard lapse rate (3.5° F. per 1000 ft.) to estimate missing temperature values, without testing it against empirical weather observations. However, Shanks (1954) concluded that the lapse rate for the Great Smoky Mountains was only 2.23° F. per 1000 feet., suggesting that some unique process may be operative within at least part of the Southern Appalachian region.

Before choosing the standard lapse rate, I had to first determine if it accurately reflected the pattern of modern weather data. To test the lapse rate, I grouped 53 Weather



NORTH CAROLINA		TOPOCO		SOUTH CAROLINA	
1	ANDREWS	34	TRYON	66	CEASAR'S HEAD
2	ASHEVILLE WSO AP	35	WATERVILLE 2	67	CLEVELAND 4 S
3	ASHEVILLE	36	WAYNESVILLE 1 E	68	HOGBACK MOUNTAIN
4	BENT CREEK	37		69	LONGCREEK
5	BLACK MOUNTAIN 2 W		GEORGIA	70	ANDERSON
6	BREVARD	38	BOWMAN	71	ANDERSON FAA AP
7	BRIDGEWATER HYDRO	39	CARNESVILLE 4 N	72	CLEMSON UNIVERSITY
8	BUCK FOREST	40	CLAYTON 1 SSW	73	GAFFNEY 6 E
9	CANTON 1 SW	41	CORNELIA	74	GASTON SHOALS
10	CATALOOCHIEE	42	ELBERTON 2 N	75	GRNVLE-SPARTBG WSO AP
11	CELO 2 S	43	HARTWELL	76	LAURENS
12	COWEETA EXP STATION	44	LEXINGTON 1 NW	77	LOCKHART
13	CULLOWHEE	45	LINCOLNTON	78	NINETY NINE ISLANDS
14	ENKA	46	TOCCOA	79	OAKWAY 3 WSW
15	FLETCHER 4 E	47	WASHINGTON 2 ESE	80	PICKENS 5 SE
16	FLETCHER 3 W	48	ALPHARETTA 5 SSW	81	SALEM 1 SW
17	FOREST CITY 6 SW	49	ATHENS WSO AP	82	SANTUCK
18	FRANKLIN	50	ATLANTA WSO AP	83	SPARTANBURG 3 SSE
19	HENDERSONVILLE 1 NE	51	BALL GROUND	84	UNION 8 SW
20	HICKORY FAA AP	52	BLAIRSVILLE EXP STN	85	WALHALLA
21	HIGHLANDS	53	CANTON	86	WEST PELZER
22	HOT SPRINGS	54	CLEVELAND	87	WHITMIRE 4 NE
23	LAKE LURE 2	55	COMMERCE 4 NNW	88	WOODRUFF 5 NW
24	LAKE TOXAWAY 2 SW	56	CUMMING		
25	MARION	57	DAHLONEGA		TENNESSEE
26	MARSHALL	58	HELEN		
27	MORGANTON	59	JASPER 1 NNW	89	ATHENS
28	MURPHY 2 NE	60	MAYSVILLE	90	CHATTANOOGA WSO AP
29	NORTH FORK 2	61	NORCROSS 4 N	91	CONASAUGA 2 N
30	OCONALUFTEE	62	U OF GA PLT SCI FM	92	GATLINBURG 2 SW
31	PISGAH FOREST 1 N	63	WALESKA	93	KNOXVILLE WSO AP
32	ROSMAN	64	WINDER 1 SSE	94	NEWPORT 1 NW
33	SWANNANOVA 2 E	65	WOODSTOCK	95	SEVIERVILLE 1 SE
				96	MT. LECONTE

Figure 4.2 Weather Stations Included in the Regional Climatic Database.

stations with all monthly temperature observations for 1988 together. This group was subdivided into three additional groups based on latitude. Using mean annual temperature observations for 1988 and station elevations, a regression analysis was performed on the regional group and the three subregional groups to determine the regression coefficients for temperature predicted by elevation. The R-square values ranged from .73 to .81 for the four groups (Appendix B). The constant for each group was used to represent the sea level mean annual temperature for the group. Predicted temperatures were then calculated at a regular interval of 500 feet up to an elevation of 6500 feet. For each group, the predicted temperatures were obtained by multiplying elevation by the X coefficient from the regression analysis. The set of predicted temperatures using this procedure was termed the regression climate.

Another set of predicted mean annual temperatures was calculated for each of the same four groups by using the standard lapse rate. The lapse rate set of predicted temperatures was developed by first determining both the average of the mean annual temperature and the average elevation for each group. The sea level mean annual temperature was then estimated by adding the average of the group mean annual temperature to the group average elevation multiplied by .0035 (the equivalent of the standard lapse rate of 3.5° F./ 1000 ft.). Once a mean sea level temperature had

been estimated for each group, then predicted temperature values were calculated by reducing the sea level group mean by the standard lapse rate ($3.5^{\circ} \text{ F.} / 1000 \text{ ft.}$) at regular 500 foot intervals up to elevations of 6500 feet. The second set of predicted temperature values was termed the lapse rate climate.

A regression analysis was performed between the predicted temperatures of the regression climate and the lapse rate climate of each group to determine if there was any significant difference between them. The R-squares for all these regression analyses was .99, indicating that there was no significant difference between the values generated by either method (Appendix B). I decided to use the standard lapse rate method, since it is much faster and easier to use. The flow of this decision making process is summarized in figure 4.3.

Once the standard lapse rate had been chosen to estimate missing temperatures, the average elevation was determined for each National Weather Service climate region. The elevation of each station was summed and the resulting sum was divided by the number of stations. The divisional temperatures were increased by multiplying the difference between the average elevation of the division and sea level by the standard lapse rate (3.5° F.) This process resulted in an estimated divisional sea level climate for each of the NWS divisional regions. The advantage of reducing the divisional climate to

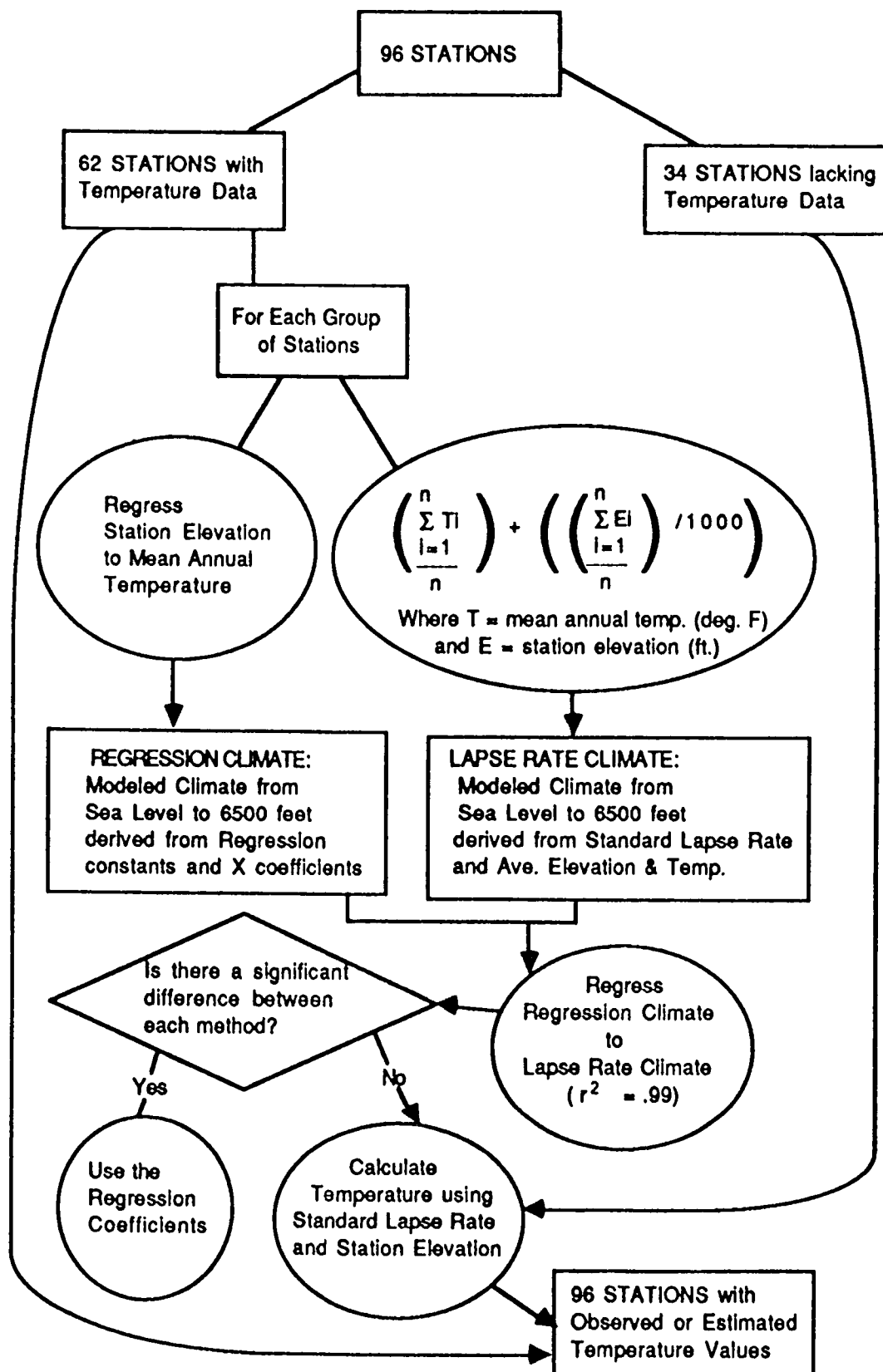


Figure 4.3 Process of Choosing Standard Lapse Rate

sea level is that every estimate will be a decrease based on elevation. If the actual divisional climate corresponding to the average divisional elevation was used, some of the estimates would be increases (when the station was at a lower elevation than the divisional average), while other estimates would be decreases (when the station was at a higher elevation than the divisional average). Using the sea level divisional climate enables a value to be estimated for any station lacking mean monthly temperature observations by taking the stations elevation and multiplying by the standard lapse rate. This product is always subtracted from the monthly temperature of the divisional sea level climate. The difference provides a reasonable estimate for missing temperature values. The procedure was used for both the long term average climate and the representative drought year of 1988.

The 53 weather stations that lacked temperature normals and the 38 stations that lacked precipitation normals were assumed to have the same monthly departure from the long-term normal as the NWS region in which they were located. In a very few cases, where an observation for either precipitation or temperature was missing, the NWS regional value was used, so that the station could be preserved within the database.

The long term climatic PE Index was calculated for all the stations using either actual precipitation and temperature values or estimates based on the regional climate model described above. The PE Index for 1988, the drought year, was

calculated using actual precipitation values. In a few instances, where a monthly value was missing, or some observations had been missed during the month, an estimated precipitation value was used. The estimated value was based on both the NWS divisional value and the closest station. The temperature values used were either actual values, or estimates based on the regional sea level climate reduced by the stations elevation using the standard lapse rate as previously described.

For each station the calculated PE values for both average conditions and drought conditions were entered as items within the PAT file of the ARC/INFO coverages. PE indices were classified according to the humidity provinces and plotted as points. The boundaries of the humidity provinces were manually drawn on the plot of station points and digitized. The resulting polygons were then used to determine the spatial extent and distribution of the Southern Appalachian perhumid area for the long term average and the drought of 1988.

4.3 Local Study Area

A GIS database was developed for a smaller study area within the Southern Appalachian region, centered at 35° 7' 30" North latitude, 83° 30' West longitude, which is in the southwestern part of Macon County, North Carolina. This localized study area is rectangular in shape, approximately 13

kilometers along the North-South axis, and 10 kilometers wide along the East-West axis. The study area is slightly smaller in area than that covered by a single USGS 1:24,000 scale map sheet. It lies at the intersection of the Rainbow Springs, Wayah Bald, Franklin, and Prentiss map sheets (Figure 4.4).

I selected this study area for the following reasons.

1. precipitation varies greatly
2. forest is the dominant land use
3. topography is varied

These conditions mimic the larger region, suggesting that the local study area may represent the larger Southern Appalachian region. Quantitative values derived from the analysis of the local database may be extrapolated to provide preliminary quantitative estimates for the larger region.

Since topography exercises local control on the location of temperate rainforests, I developed a topographic data layer for inclusion in the localized GIS database. The USGS 1:24,000 Topographic maps of the local study area were analyzed manually in order to select all cove and moderate slopes with a Northern or Eastern aspect. Coves were areas with slopes of less than 15% over a minimum length of 500 feet. Slopes greater than 15%, but less than 25% were considered to be moderate. The moderate slopes also had to have a Northerly or Easterly aspect. Since the cove forests are restricted to areas less than 4000 feet in elevation, the areas above this contour were also identified. The selected

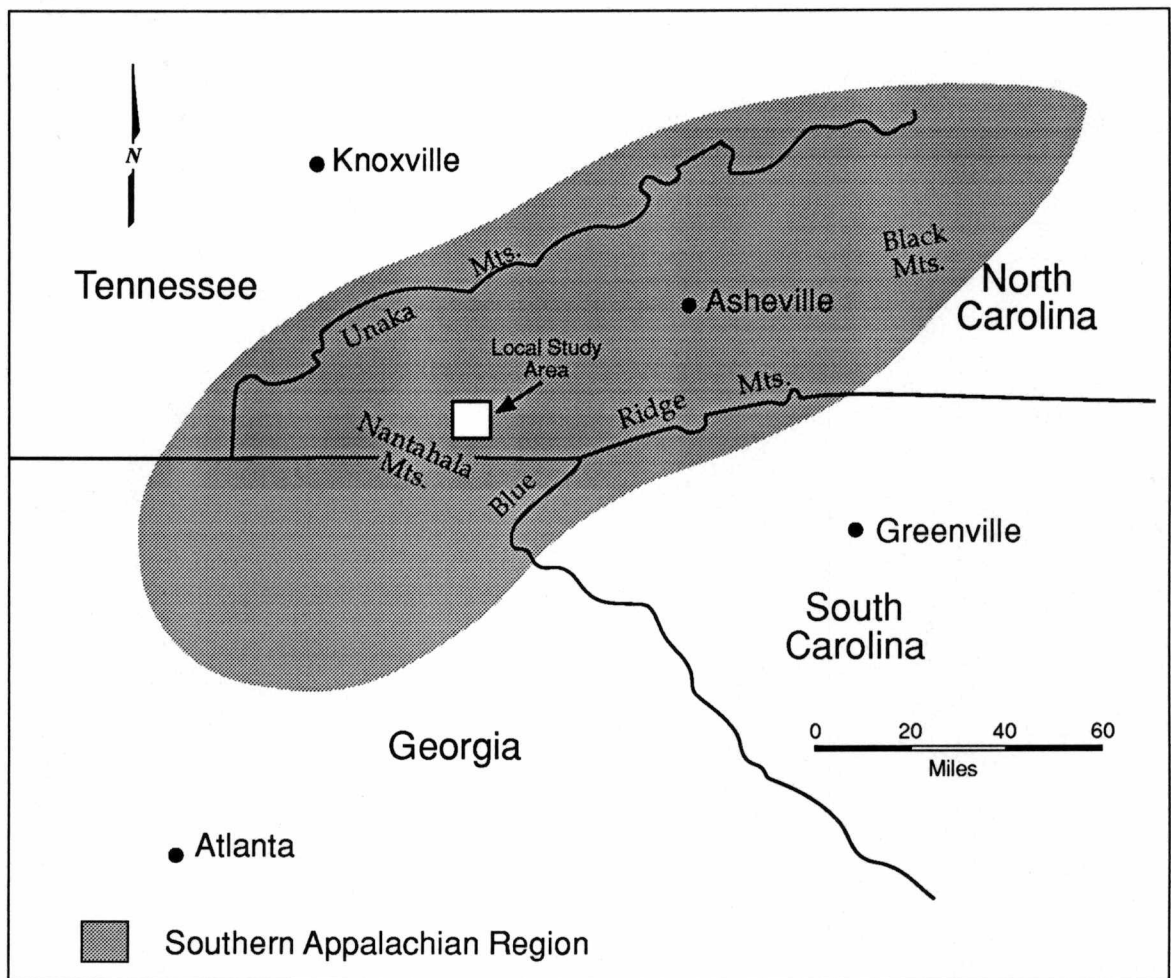


Figure 4.4 The Local Study Area Within the Southern Appalachian Region

areas were drawn on a manuscript and then digitized into an ARC/INFO coverage. The topographic coverage was exported to an ERDAS GIS file containing four topographic classes, namely potential rainforest slopes, potential rainforest coves and valleys, potential general forest terrain, and potential high elevation forest.

4.4 Image Processing

Satellite data has been recognized as an essential component for monitoring resource features over extensive land areas (Meyer and Werth, 1990). While the local study area is much smaller than the whole region, it still represents a considerable land area and satellite data were required to develop data layers corresponding to land use and vegetation cover types.

A rectified, georeferenced 1990 Landsat Thematic Mapper (TM) satellite image (taken during July), was used to develop the land use and vegetation layers for the local database. This TM image had been resampled to 25 meter pixel size for all seven bands, including band 6 that normally has a 120 meter pixel size (Table 4.1). The 1990 TM image was processed using ERDAS software to develop a digital map of general land use and a more detailed digital map of forest types. The general land use map was generated in several phases. The first two phases both used an unsupervised sequential clustering algorithm, the only difference being the TM bands

TABLE 4.1
Landsat Thematic Mapper Bands

Band #	EM energy	wavelength (μm)
1	Blue (visible)	0.45-0.52
2	Green (visible)	0.52-0.60
3	Red (visible)	0.63-0.69
4	Reflective Infrared	0.76-0.90
5	Mid-Infrared	1.55-1.74
6	Thermal Infrared	10.40-12.50
7	Mid-Infrared	2.08-2.35

Source:

ERDAS, Inc., 1990. *ERDAS Field Guide*, Version 7.4
ERDAS, Inc., Atlanta, Georgia.

contained in the ERDAS lan file. The first phase contained bands 2, 3, and 7, and the second phase contained TM bands 4, 5, and 6. The selected bands and processing technique of the first two phases produced digital maps that effectively differentiate land use and vegetation patterns.

The third phase used an unsupervised statistical clustering algorithm with TM bands 1, 2, and 7 and 1, 6, and 7. The selected bands and processing technique of the third phase are very effective at identifying linear features such as road networks. They also separate bright cloud covered areas from bright urbanized areas. The individual maps of each phase were recoded and combined to produce a final land use map containing eleven land use classes that were later simplified into five classes, including cloud covered areas and cloud shadows.

The map of forest types was generated by combining the

infrared bands 3,4,5 into an ERDAS lan file for which clouds and cloud shadows have been masked out. The image was then processed using RGB clustering to classify the pixels. This method is very effective in determining detailed variations within the vegetation.

Field work was conducted in July and August of 1992, to access the accuracy of the digital land use and forest maps. This field work involved ground-truth for selected land use and forest classes. A color laser hard copy printout of the maps, with an overlaid UTM grid was used in the field, in conjunction with 1:24,000 USGS topographic maps. The ground-truth work was limited to areas that were easily accessible by automobile, or short hikes. To insure accuracy in more remote areas, I also examined U.S. Forest Service 1:24,000 aerial photographs from March 17, 1986 at the Wayah Bald Ranger station. I also interviewed the Macon County Land Records Manager, Terry G. Breedlove, who has extensive knowledge of the land use patterns in the local study area.

The digital maps derived from the topographic maps were exported from ARC/INFO coverages into ERDAS GIS files and combined with the digital maps derived from the satellite images. Once the local database had been assembled within ERDAS, the information was analyzed to determine the current land uses of the topographic classes favorable for the development of temperate rainforest. The forested cove and slope sites were compared to other forested topographic sites

to determine if there were any differences in the vegetation patterns between these areas.

Eleven randomly selected sites were selected from among the potential rainforest formation topographic classes (slopes and coves), and eleven were selected from the general forest terrain topographic class that would not be expected to support forests exhibiting rainforest characteristics. Forest was the land use class for each site. A file corresponding to each site was extracted from an image file containing all seven TM bands. Each of these image files contained 56 pixels, representing 3.5 hectares. Each site file was processed with an unsupervised classification using a sequential clustering algorithm with a maximum of two clusters allowed. The results of this process were analyzed to determine which TM bands had the greatest variations between the potential rainforest topographic classes and the non-potential rainforest classes. The goal was to determine if there was a unique spectral signature that could distinguish the potential rainforest sites (slopes and coves) from the general forest topographic class.

Existing mature and old-growth coniferous forests have been distinguished in the Pacific Northwest using a wetness index based on the ratio between TM Bands 4 and 5 (Fiorella and Ripple, 1993). The ERDAS algebraic functions were used to create new images based on the ratios between the TM bands with the greatest variations between the two sets of sites.

This process serves to amplify the differences between the two sets of sites. The expressions are:

1) output band 1: $(\text{TM band 6} - \text{TM band 5}) * 2$

2) output band 2: $(\text{TM band 6} / \text{TM band 3})$

3) output band 3: $(\text{TM band 5} - \text{TM band 6}) * \text{TM band 3}$

The output image file from this procedure was then processed using a standard sequential clustering algorithm with a maximum of twelve allowable clusters. Cloud and cloud shadows had been previously masked out of the input images. The resulting GIS files were then overlaid with the topographic GIS file to determine if the transformed images contained a class or classes that correlated with the potential rainforest areas identified by the topographic model. This process was designed to determine if a spectral signature could be found that effectively identifies potential rainforest areas from the selected Landsat TM image.

CHAPTER 5

RESULTS

5.1 Average Perhumid Climate

Analysis of the 30 year mean temperature and precipitation data assembled or estimated for 96 Southern Appalachian weather stations using the 1931 Thornthwaite method resulted in a range of PE indices from 78 at Asheville, North Carolina to 338 at Mt. LeConte, Tennessee (Appendix C). 21 stations had a PE index above the 128 threshold required for inclusion within the perhumid class. 16 additional stations had PE indices in excess of 112, values that put them in the upper quartile of the humid class. This upper quartile can be considered a near perhumid class. Under average conditions no stations had PE indices corresponding to the subhumid class, although several in the Asheville Basin and the South Carolina Piedmont were in the lowest quartile of the humid class (64-80).

The elevations of perhumid class stations ranged from 910 ft. to 6493 ft., while those of the humid class stations ranged from 400 ft. to 2662 ft. This indicates that elevation has a positive relationship to PE indices values, but elevation alone cannot explain the observed variation in PE indices. The distribution of the PE indices in relation to elevation is shown in Figure 5.1.

Under average conditions, the area of the Southern

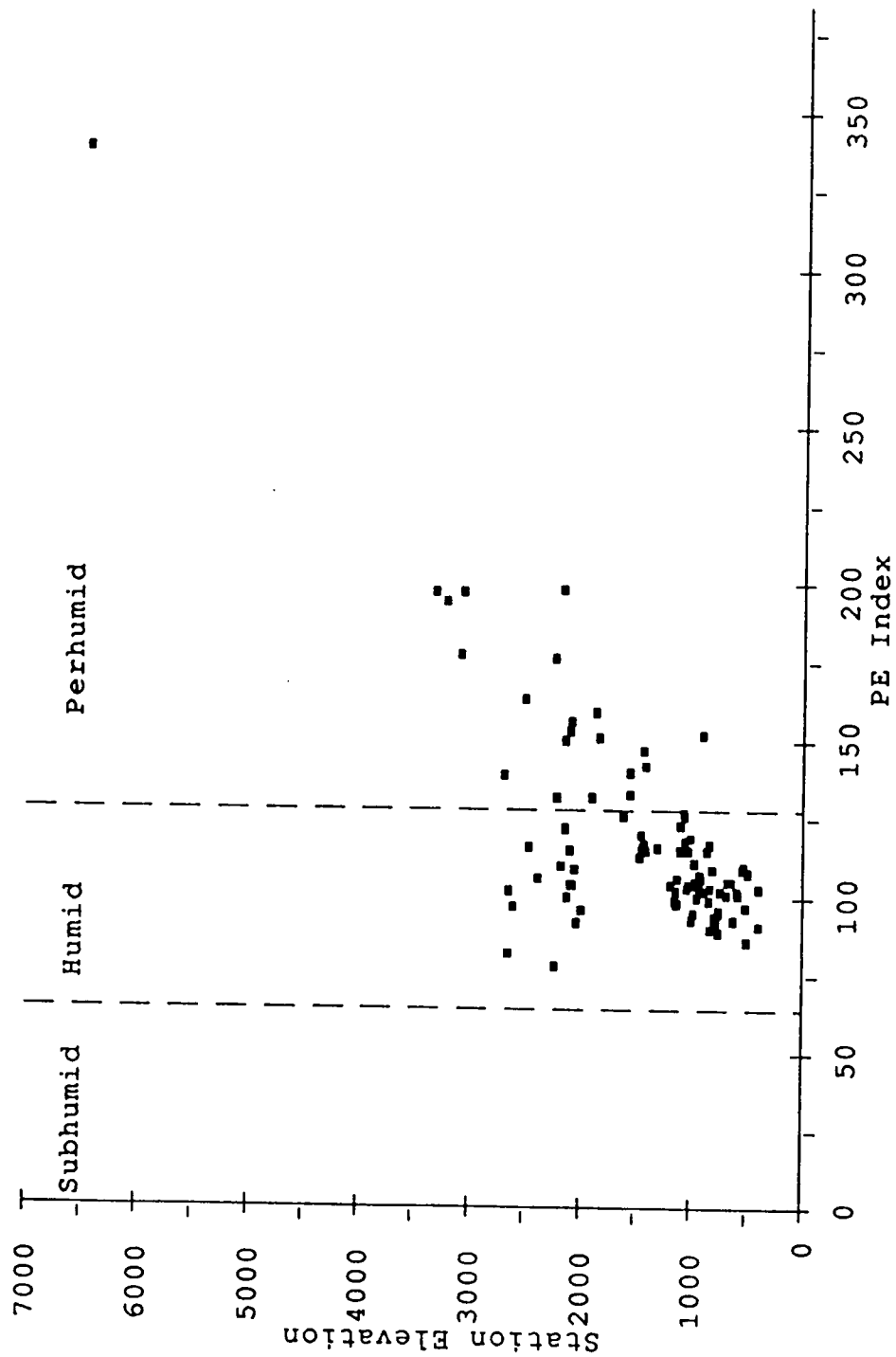


Figure 5.1 Average PE Indices and Elevation

Appalachian perhumid climate area covers approximately 5194 square miles, with an additional 4215 square miles of near perhumid climate (PE Index greater than 112) on the perimeter of the primary perhumid climate (Figure 5.2).

5.2 Perhumid Climate During Drought Conditions

Analysis of the 1988 observed or estimated data for 96 Southern Appalachian weather stations using the Thornthwaite method produced a range of PE indices from 45 at Asheville, North Carolina to 216 at Mt. LeConte, Tennessee (Appendix C). Under drought conditions, only five stations exceeded the 128 threshold required for inclusion in the perhumid class. Six other stations had PE indices in the upper quartile of the humid class, and thus were near perhumid under drought conditions. If the threshold of the near perhumid class is lowered to 100, then ten additional stations are added. The boundary of the stations with PE Indices between 100 and 128 under drought conditions closely resembles the boundary of the perhumid class under normal conditions (Figure 5.3).

During drought conditions, the PE indices for ten stations were below the threshold of 64 for inclusion in the subhumid class. Two of these ten stations, Asheville and Enka, actually had PE indices typical of the dry subhumid class (Figure 5.4).

Under drought conditions, the elevations of perhumid class stations ranged from 2180 ft. to 6493 ft., while the

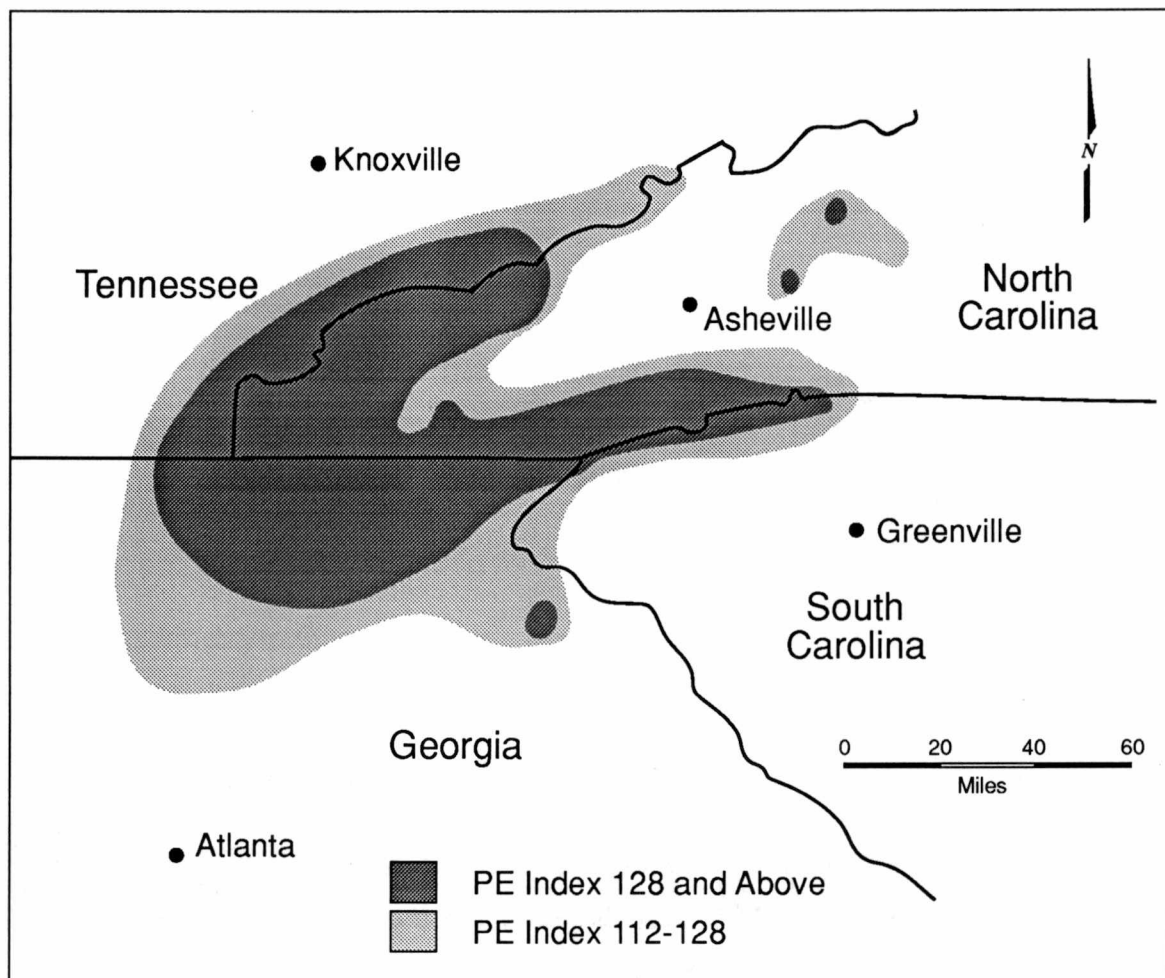


Figure 5.2 Perhumid Climate Regime of the Southern Appalachians During Average Conditions (Period 1951-1980).

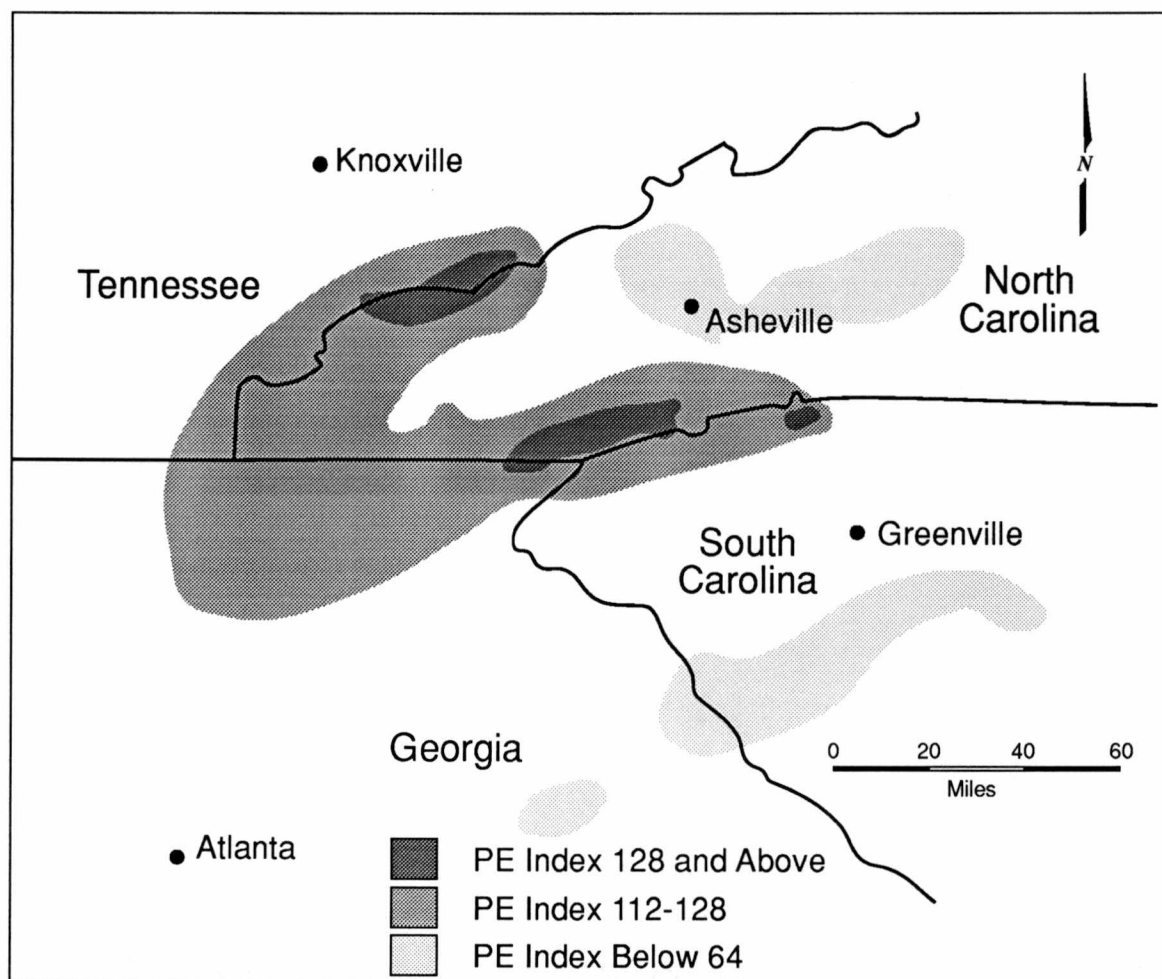


Figure 5.3 Perhumid Climate area During Drought Conditions, 1988

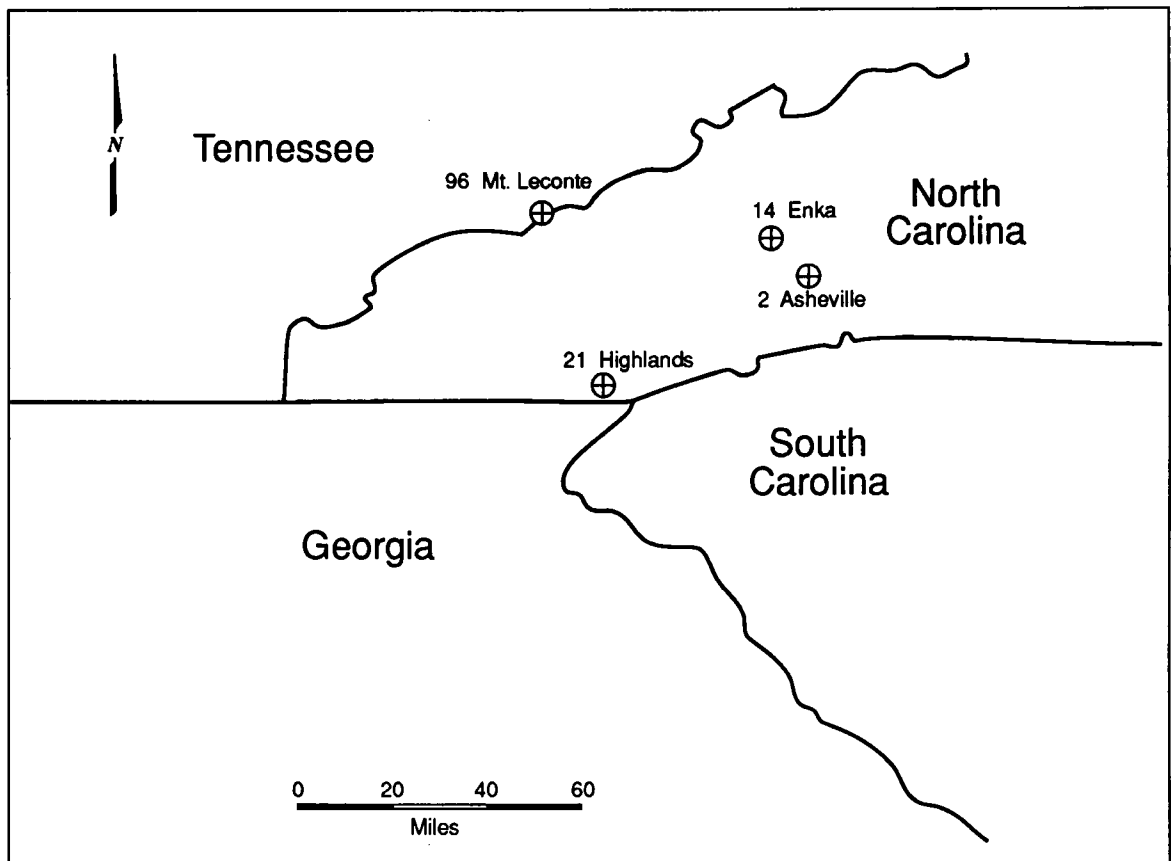


Figure 5.4 Selected Stations in the Southern Appalachian Region

subhumid class elevations ranged from 760 ft. to 2242 ft. The distribution of PE indices in relation to elevation during drought conditions are summarized in Figure 5.5.

The analysis of the 1926 climate data for Asheville and Highlands produced PE indices of 48 and 129 respectively. The PE index for Asheville compares favorably with the 1988 Asheville PE index of 45, however the 1926 PE index of 129 for Highlands is much lower than the 1988 PE index of 184. While precipitation totals during both of these drought years were comparable, the temperatures in 1926 were much warmer than 1988. These warmer conditions apparently resulted in a much more intense drought, which is reflected in the lower PE index for Highlands.

5.3 Topographic Model of the Local Study Area

In the local study area that covers approximately 50 square miles, I identified 8.75 square miles of cove and valley sites favorable for the development of temperate rainforest formations (Plate 7). These cove and valley sites represent 17.5 percent of the local study area. I also identified 2.2 square miles of moderate slopes that would be favorable for the development of temperate rainforest formations. These moderate slopes account for 4.4 percent of the local study area.

Almost 70 percent of the local study area was classified as general terrain. This general terrain may contain smaller

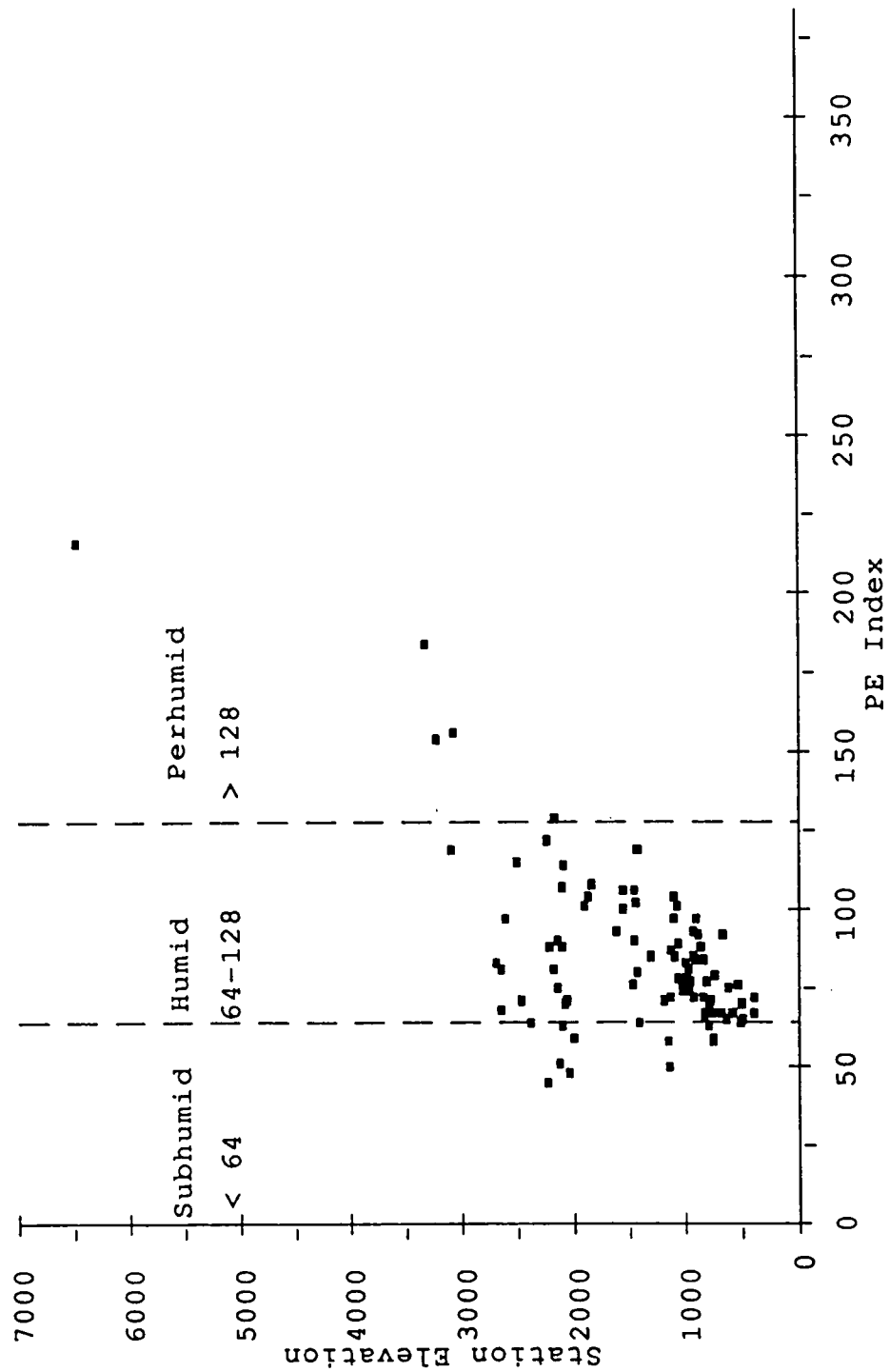


Figure 5.5 1988 PE Indices and Elevation

coves or slopes suitable for temperate rainforest vegetation, but shows no explicitly favorable topographic conditions.

I identified 8.7 percent of the local study area as high elevation sites that are unfavorable for temperate rainforest formations based on the parameters of Appalachian cove forests. The results of the topographic analysis of the local study area are summarized in Table 5.1.

5.4 Land Use in the Local Study Area

The digital map of land use classes derived from the 1990 TM image indicates that the overwhelming land use within the local study area is forest -- accounting for 73 percent of the area (Plate 8). Urban land uses and transportation make up an additional 13 percent of the land use. Agriculture and open pasture only account for six percent of the area. The remaining land area was covered by clouds and cloud shadows on the TM image and could not be classified (Table 5.2).

TABLE 5.1
Topography in the Local Study Area

Topographic Setting	Percent	Sq. Miles
Coves & Valleys	17.5	8.75
Moderate Slopes	4.4	2.20
General Terrain	69.4	34.70
High Elevation	8.7	4.35

Total	100.0	50.00

TABLE 5.2

Land Use in the Local Study Area

Land Use Class	Percent	Sq. Miles
Transportation	3.7	1.85
Urban	9.3	4.65
Agriculture	5.7	2.85
Forest	73.0	36.50
Unclassified	8.3	4.15
Total	100.0	50.00

The overlay of the land use map with the topographic map within the GIS yielded additional information about the land use patterns of the local study area. In the cove and valley sites forested areas only accounted for 51 percent of the land use. These same cove sites, which only account for 17.5 percent of the local study area, include 37 percent of urban land use for the local study area as a whole. Land use in the slope sites favorable for temperate rainforest formations consists of 84 percent forest and only 9.9 percent urban (Table 5.3).

5.5 Forest Types in the Local Study Area

The overlay of the topographic settings and the digital vegetation map (Plate 9) derived from the TM satellite image revealed that mesic hardwood forest comprises 41 percent of the forested slope sites and 38 percent of the forested cove

TABLE 5.3

Classified Land Use by Topographic Class
in the Local Study Area

Land Use Class	Slopes: Percent	Share ¹	Coves: Percent	Share ¹
Transportation	4.4	4.5	7.7	35.5
Urban	9.9	4	20.5	37.2
Agriculture	1.9	1.3	20.3	60.7
Forest	83.9	6.5	51.4	28.3
Total	100.0		100.0	

¹share: For each topographic class, the percentage share of that land use class for the whole local study area.

forest class is the most abundant forest cover type. Mixed hardwood and hemlock forest accounts for 23 percent of the forested slope sites and 20 percent of the forested cove sites. Oak forest comprises 25 and 22 percent respectively of these same topographic settings.

The forests of the general forest topographic class included almost equal percentages of mesic hardwoods (32.3) and oak forest (31.2). They also differed from the slope and cove sites in having more pine and mixed oak and pine. Oak forests (38.1) are the most important forest type in the high elevation sites, and when combined with the xeric oak forest (13.5), they comprise over half the forested area.

5.6 Spectral Signatures

The spectral signatures from the eleven topographically favorable temperate rainforest environment sites, i. e. slopes and coves, showed consistently different values from the eleven non-favorable temperate rainforest environments. The differences between them were most pronounced for TM band 6 (thermal infrared), and TM band 5 (mid-infrared), but there is more variation in the range of individual pixel values in all seven TM bands for non-favorable rainforest environments. However, the difference between the average pixel reflectance values for these two sets is not significant. The spectral signatures from the 1990 TM image failed to provide an effective means of identifying favorable rainforest environments from TM satellite imagery alone. The three-band synthetic output image file produced using the algebraic expressions on input from TM bands 3, 5 and 6 also failed to identify a distinctive difference between spectral signatures of favorable rainforest environments and non-favorable rainforest environments.

5.7 Combined Regional and Local Results

Based on the overlay of the average perhumid climate region and local study area, 87 percent of the local study area has a perhumid climate. Within this perhumid climate zone, 20 percent of the land has topographic settings favorable for the development of a temperate rainforest

formation. Table 5.4 summarizes the distribution of the topographic classes within the local study area and within the two climatic classes.

Extrapolation of the results from the local study area suggest that 20 percent of the Appalachian perhumid climate region would have topographic environments capable of supporting cove forests exhibiting characteristics typical of temperate rainforest formations. These environments would cover slightly over 1000 square miles and would constitute a temperate rainforest ecosystem.

TABLE 5.4

Distribution of Topographic Classes in Relation to Climatic Classes within the Local Study Area

Topographic Site	Perhumid	Humid	Whole Area
<u>Favorable:</u>			
Slope	5.3	2	4.4
Cove	14.9	23.6	17.9
- - - - -	- - - - -	- - - - -	- - - - -
Subtotal	20.2	23.8	21.9
<u>Non-Favorable:</u>			
General Terrain	67.9	76.2	69.4
High Elevation	11.9	0	8.7
- - - - -	- - - - -	- - - - -	- - - - -
Subtotal	79.8	76.2	78.1
<u>Favorable and Non-Favorable:</u>			
Total	100	100	100

CHAPTER 6

DISCUSSION AND CONCLUSIONS

6.1 Moisture Indices

The Thornthwaite (1931) method applied in the context of a Geographic Information System is capable of differentiating variations in regional climatic moisture regimes that exert a strong control on forest vegetation patterns. This method was used in this study, since the moisture classes associated with this system relate directly to changes in vegetation formations.

In the system published in 1948, Thornthwaite added more moisture classes but did not specify the associated changes in vegetation expected with these additional moisture classes. For example, the 1931 humid class, for which PE indices ranged from 64 to 128, is characterized by forest vegetation. The equivalent limits for this 1931 humid class expressed in 1948 PE index units would be 20 to 100. However, the 1948 version subdivides this range into four classes based on an interval of 20 units, without explaining the vegetational changes expected for each interval.

Thornthwaite and Mather (1955) presented another method for calculating the moisture index that is more useful for hydrological studies, since it involves a soil moisture storage variable. This method may be useful in GIS applications for a more localized territory for which digital

soil data are available.

Wilmott and Feddema (1992) presented a modified version of the Thornthwaite moisture index that is symmetrical about zero. This method facilitates contour mapping with a constant interval for both wet and dry climates. However, the mapped contours do not represent different climatic types. Thus, this system would be most useful for comparative climatic analyses at the global or continental scale.

Since the objective of this study was to identify climatic differences that were related to vegetational differences at the regional scale, I chose the 1931 Thornthwaite system as the method that best met my objectives. Several of the other described moisture methods may be valuable for other GIS applications.

6.2 Perhumid Climate

Under average conditions, the Southern Appalachian perhumid climate regime develops in response to orographic enhancement of the precipitation process. However, the spatial extent of this area is not strongly correlated to elevation alone. In northeastern Georgia, several stations below 1000 ft. elevation are included, while in the Asheville Basin of North Carolina several stations above 2000 ft. are not. Apparently the situation of a station in relation to the major mountains ranges of the region plays an important role in determining the precipitation amounts. The mountains

interrupt the prevailing west and south winds. Thus, the Asheville Basin, despite its considerable elevation, is sheltered from west winds by the Unaka mountains, and south winds by the Blue Ridge mountains, resulting in relatively dry conditions. In essence, it occupies a rainshadow. On the other hand, northeastern Georgia, despite its relatively low elevation, is exposed to both the west and south winds. The airmasses must begin to be uplifted on their approach to the Unakas and Blue Ridge.

The shape of the whole perhumid climate area is reflected in this process, since it is broadest in the southwest and tapers off into two tails, each of which extend northeastward along the two primary mountain ranges. A few outlier islands of perhumid climate are found among the high peaks of the Black Mountains to the northeast. The perhumid climate area of the region is not simply a function of elevation. The 2000 foot contour may represent the perhumid climate boundary in the Smoky Mountains (Shanks, 1954), but it does not represent the boundary throughout the region.

During drought conditions, the larger perhumid climate area dissolves into several smaller islands that are oriented along the main crests of the Unaka and Blue Ridge Mountains. A near perhumid area has almost the same spatial extent as the average perhumid area. During drought conditions all the stations in the Black Mountains fall out of both the perhumid and near perhumid class. The more pronounced drought

conditions in the Black Mountains may account for the cove forests there having a lot of chestnut before the blight, and now oak species typically associated with drier slopes.

Also notable is the development of subhumid conditions in the Asheville Basin and parts of the Piedmont. During drought conditions, the PE indices reveal that vegetation within the region experiences a much greater range in moisture conditions, varying from perhumid to dry subhumid. Pine is an important component of the forests in both of these areas, and may be favored by the variation in moisture conditions. (Figure 6.1).

The limited comparative data from the 1926 drought indicate that similarly wide ranges of moisture conditions probably occur during other droughts. However, the dry conditions during 1926 were accompanied by much warmer than normal temperatures, and subhumid conditions may have covered a much larger territory. Fires were very widespread during the 1926 drought. In the absence of a fire-suppression policy, they probably also would have been widespread during the 1988 season.

6.3 Topography of the Local Study Area

Within the local study area, the favorable topographic sites for temperate rainforest formations (combined area of coves and slopes) amounted to approximately 11 square miles, or 22 percent of the total area. This value for topographic

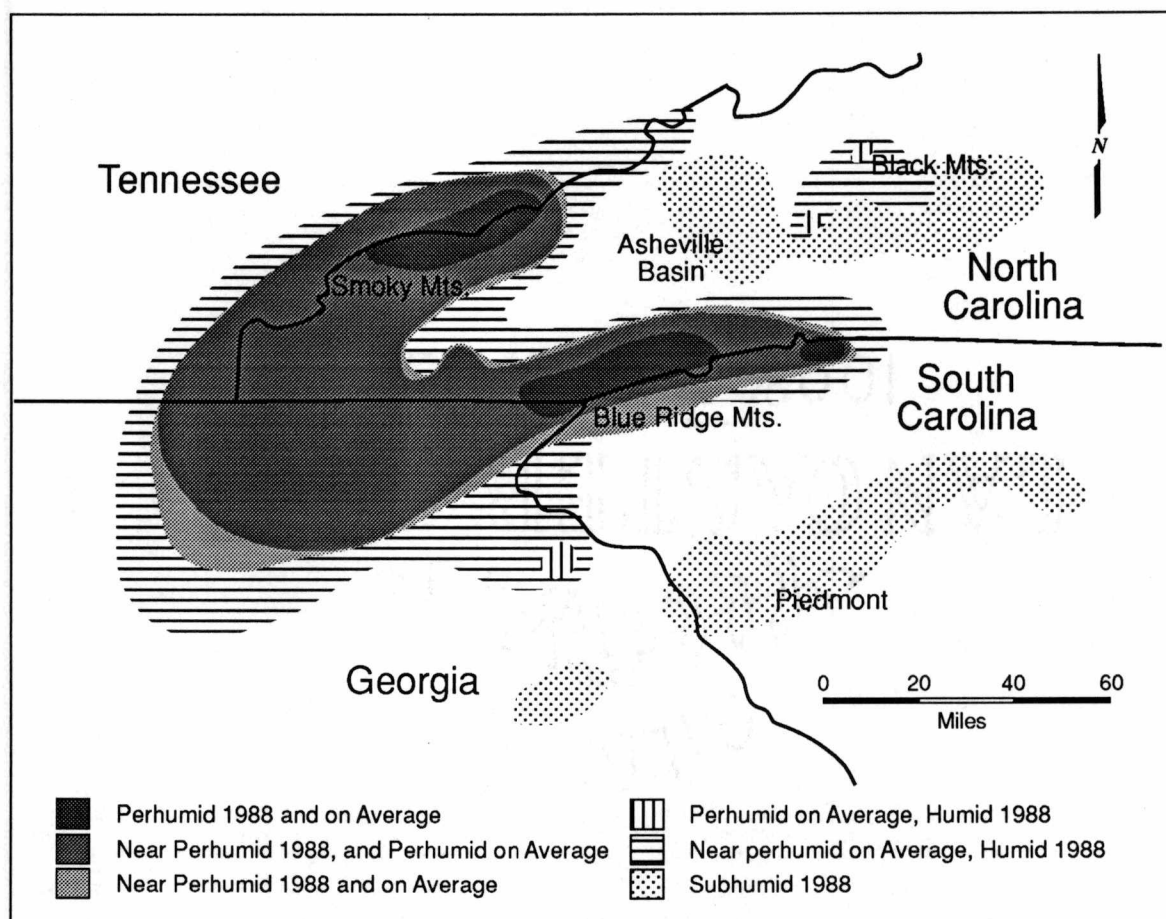


Figure 6.1 Overlay of PE Indices for 1988 and Average Conditions

sites is less than the estimate by Stuart and Frothingham (1926) that one-third of the Southern Appalachian region consisted of cove hardwood forests. It is also less than the 33.4 percent cove forest MacKenzie (1989) found for the Great Smoky Mountains National Park. While these identified topographic classes cover less area than expected of cove forests, the site parameters are not designed to be coextensive with actual stands of cove forest. The model sites exclude some areas that could support cove forests of lower quality, such as moderate slopes with east and south aspects. The topographic sites were derived from manual analysis of USGS map sheets, and the threshold slope length of 500 ft. may also have missed some areas with shorter slope length. Some smaller cove sites may also have been missed. Ideally, the topographic classes could have been derived from Digital Elevation Models (DEMs). However, despite the availability of DEMs, hardware and software limitations precluded their use for this thesis project. Future research work should use DEMs to digitally analyze topography. The manual topographic analysis method used here was still able to effectively identify the area containing the Wasilik Poplar, an approximately 11 ft. diameter specimen of tulip poplar that is one of the largest trees in the region. Thus, the largest and most distinctive coves and slopes have probably been identified, though smaller areas may have been missed. Alternatively, digital topographic analysis of DEMs may

identify an excessive number of small areas that may have to be later filtered out. The manual topographic analysis method may offer an advantage in this regard. The greater extent of cove forest found in previous studies, in comparison with the favorable topographic sites identified in this study, suggests that if the 22% figure is in error, it may be a conservative underestimate.

6.4 Local Patterns of Land Use and Forest Types

The pattern of land use within the local study area was fairly typical of the region as a whole. Forest accounts for most of the land cover for the region as a whole, just as it did in the local study area. The urban class within the study area appears to be higher than the average for the region, but that is only because I used a fairly broad definition for the urban class. In essence, the urban class includes both truly urban areas, and the less densely settled suburban and rural areas with many home sites. As expected, urban land use was more widespread in cove and valley sites, compared to the slope and general terrain classes. In general, the 50 square miles of the local study area represent a good sample of land use patterns for the larger region.

The forest vegetation patterns in relation to topographic site were very typical of the region as a whole. Oak forests are the most important type in the highest elevation class of the ridges. The mesic hardwoods are the most important type

on the slopes and to a slightly lesser degree on the cove sites. Undoubtedly, the cove sites have a reduced mesic hardwood cover because of human disturbance and reduced forest cover in general. The vegetation patterns discerned from the combination of TM imagery and the topographic sites suggest that the local study area is representative of the vegetation patterns of the Southern Appalachian region.

6.5 Spectral Signatures

The attempt to identify a spectral signature that could uniquely identify temperate rainforest environments from the 1990 TM satellite image was not successful. This result suggests that TM imagery must be combined with other data within a GIS database in order to identify these environments. However, considering the extreme range in moisture conditions found in the region during drought conditions, it may still be possible to extract an identifying spectral signature from a TM image taken during drought conditions. The prevailing moist conditions during 1990 may have effectively masked the temperate rainforest environments. Unfortunately, I did not have access to such an image. Future research using TM images taken during the drought from 1986 to 1988 may lead to the identification of a spectral signature.

Also, the 1990 image used in this study had been preprocessed by georeferencing, rectifying, and resampling to 25 meter pixels. While such a preprocessed image offers

advantages in terms of convenience, the rectification process may reduce the utility of the image. The resampling algorithms used in rectification alter the pixel values and can result in a less spectrally correct image (ERDAS field Guide, 1990). Any future attempts to distinguish temperate rainforest environments from TM imagery should probably make use of raw unrectified images.

In addition, the conversion of almost 50 percent of the favorable cove forest areas in the local study area to non-forest land uses may have already eliminated the forest sites with the most pronounced spectral signatures. If true, this possibility suggests that even TM images from drought years may be ineffective at identifying temperate rainforest environments. Ultimately, the optimal solution may require the development of a detailed digital database for the whole region.

6.6 Extent of Temperate Rainforest

The extrapolation of the local study area results to the larger perhumid climate area of the Southern Appalachian region is based on the assumption that this local study area is, in fact, truly representative of the region as a whole. Any error in this assumption has the potential to undermine the conclusions developed for the whole region. This source of potential error could be completely avoided if the resources were available to develop a thoroughly detailed

database for use within the GIS.

Development of this type of database would be an important step in finding an optimal solution to identifying temperate rainforest environments in the Southern Appalachians. However, the goal of this study is to find an heuristic solution to this question. I am by no means suggesting that such a solution allows one to lightly dismiss this issue. Rather, the end product of this analysis using GIS, as with all output from GIS, should be critically evaluated in relation to empirical evidence. Ultimately, every GIS project is limited by the quality of the data--digital or otherwise. Geographic analysis always involves generalization, reduction and simplification of the complexities of the real world, whether GIS is used or is not used. The application of GIS to geographic analysis requires special caution. One can never be too careful in a digital environment. Data integrity can be seriously compromised, altered, and even lost. Error can unwittingly be introduced to the database. Thus, the results achieved should be critically evaluated to determine if they fall within an acceptable range of accuracy, while simultaneously recognizing that they may never be as precise as ideally desired.

Realistically, the percentage of topographic sites favorable for the development of temperate rainforest formations will vary across a region as large as the Southern Appalachians. However, keeping in mind that the land use and

forest vegetation patterns for the local study area closely reflect those same patterns for the whole region, then it is reasonable to expect that the pattern of topographic sites for the local study area should fit the regional pattern. Alternatively, how likely is it that the local study area could mimic regional land use and forest vegetation patterns, and yet have a radically different pattern of topographic sites? I would argue that it is highly unlikely.

Therefore, recognizing that this extrapolation is reasonably accurate, 20 percent of the perhumid climate area of 5200 square miles of the Southern Appalachian region is a temperate rainforest environment. This Southern Appalachian temperate rainforest environment therefore covers slightly more than 1000 square miles. Spatially, it is likely distributed in discontinuous patches through out the low and moderate elevations within the region.

6.7 The Appalachian Rainforest Formation

Are the cove forests of "exceptional quality" truly representative of an Appalachian temperate rainforest formation? They certainly have most of the distinguishing traits of temperate rainforest formations. Big trees of record girth, height, and age for their respective species are a common characteristic of these cove forests. They also have nurse logs, colonnades and stilted trees. They definitely have multiple canopies, though the abundance of lianas and

epiphytes is probably less than the average for temperate rainforests. They also exhibit a dense undergrowth of mosses, lichens, and ferns typically associated with temperate rainforests. Finally, and perhaps most significantly, the biodiversity of the Appalachian cove forests meets or exceeds that of any other temperate rainforest.

If these Appalachian cove forests represent a temperate rainforest, why has it not been previously recognized? Both Braun (1950) and Whittaker (1956) recognized the special character of these cove forests. Ironically, Braun (1950) considered them the best example of the mixed mesophytic forest type, despite the fact that they were outside of her mixed mesophytic forest region. She also noted that the cove forests of the Black Mountains were not as rich, and contained communities more typical of drier slopes. This observation fits very well with the results of the regional climatic analysis, since the low and moderate elevations of the Black Mountains fall outside the average perhumid climate regime, and approach subhumid conditions during droughts (Figure 6.1).

Previous researchers may have failed to recognize the "exceptional" cove forests as a temperate rainforest formation because by the time they studied in the region only remnants of the primeval cove forests were left. Even the gross underestimation of timber volumes by Ayres and Ashes (1905) suggest that few, besides the lumbermen, realized the quality of these cove forests, even fairly early in the century.

Shanks (1955) concluded that a rainforest climate prevailed above the 2000 ft. contour in the Smoky Mountains, but did not explicitly state that the vegetation itself represented a temperate rainforest. Similarly, the climate map of North America produced by Thornthwaite (1948) showed a perhumid climate area in the Southern Appalachians but made no specific mention of its relationship to the vegetation of the region.

Based on the results of the regional climatic analysis, and the character of the notable cove forests of the region, the cove forests of the perhumid climate region represent a summer-green temperate rainforest formation. All the exceptional cove forest locations, whether historically documented or still remaining, are found within the perhumid climate area of the region (Figure 6.2). This Appalachian rainforest formation is an important component of the ecosystem of the region, contributing significantly to the biodiversity of the region. It comprised slightly over 1000 square miles in Georgia, North Carolina, South Carolina, and Tennessee. Few undisturbed remnants of this formation have survived the human impacts of the past two centuries.

Conservation efforts should seek to restore some of these temperate rainforest environments to their former role and function within the larger context of the ecosystem of the Southern Appalachian region. The ecological niches beneath the canopy of this temperate rainforest formation may be

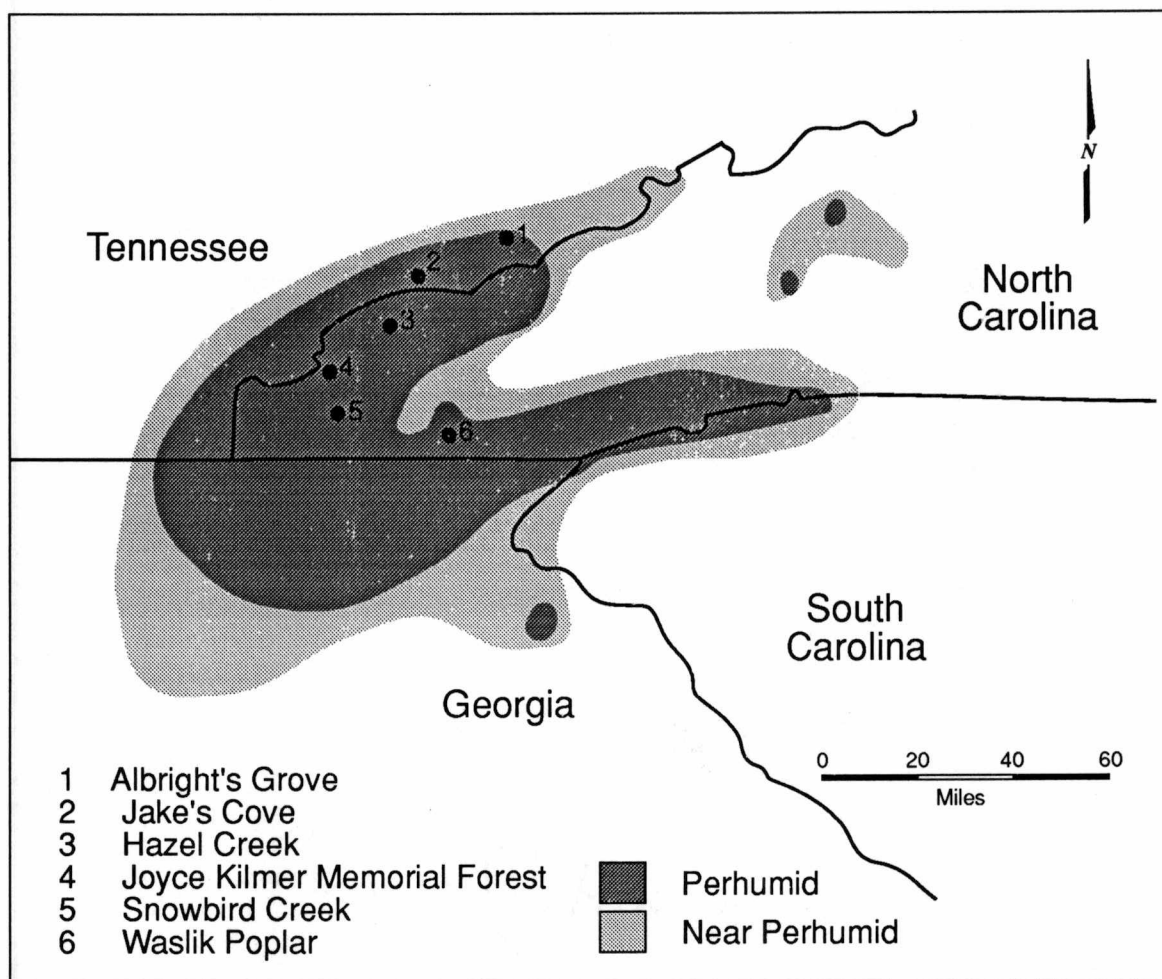


Figure 6.2 Locations of Exceptional Cove Forests

essential habitat to many of the understory species. The pattern and extent of disturbances during the past two centuries may have greatly reduced and fragmented the habitat of these species. Restoration efforts would have to involve more than just prohibiting logging of the large trees. Active management, including the planting of rare and endangered species, may be appropriate.

In other instances, the species canopy composition may have been greatly altered by disturbance. For example, the percentage of tulip poplar is much greater than would have been found under primeval conditions. Selective cutting of excessive tulip poplar may be in order. The cut trees may also be left in situ to serve as nurselogs. Some locations may need to be replanted with seedlings of species that were commercially valuable, but were unable to reproduce vigorously after disturbance.

Additional research will be required to better understand the role and function of these temperate rainforest environments within the ecosystem of the region prior to embarking on an ambitious restoration policy. The increased attention being given to the preservation of global biodiversity suggests that research related to restoration of temperate rainforest environments should be an integral part of conservation efforts in the Southern Appalachian region. Such research could contribute significantly to ensuring the future diversity and integrity of Appalachian ecosystems.

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APPENDICES

APPENDIX A

Plate 1

Well Developed Understory

The verdant herbaceous growth during the midsummer season at the Joyce Kilmer Memorial Forest near Robbinsville, North Carolina, exemplifies the luxuriant understory of temperate rainforest formations. The presence of a well-developed understory in temperate rainforest formations contrasts sharply with the typical situation found in tropical rainforests. The reason for this difference is not entirely clear.



Plate 2

Giant Tulip Poplar Tree

The temperate rainforest is characterized by exceptionally large trees, in terms of both diameter and height. This tulip poplar (*liriodendron tulipifera*) in the Joyce Kilmer Memorial Forest is fairly representative of mature tree size of temperate rainforest formations. Note the yellow 12 inch ruler in the foreground, indicating that the tree is approximately seven foot in diameter at breast height.



Plate 3

Canopy Gap formed by Windthrow

The deep shade of the temperate rainforest is occasionally broken up by fairly sizable canopy gaps produced when storms knock down the very large trees of the canopy, allowing bright sunlight to penetrate to the forest floor. Many shade-intolerant tulip poplar (*Liriodendron tulipifera*) seedlings are colonizing this gap in the Joyce Kilmer Memorial Forest. While windthrow events occur at irregular intervals, they nonetheless occur frequently enough to allow many shade-intolerant tree species to persist in temperate rainforest environments.



Plate 4

Nurse Log

Killed by the Chestnut Blight (*Endothia parasitica*), a dead chestnut (*Castanea dentata*) tree has become a moss-covered nurse log providing a home for seedlings. A small rhododendron (*Rhododendron sp.*) has established itself on this particular log. Not readily visible within the verdant covering of moss however, are many small hemlock (*Tsuga canadensis*) seedlings that have also established themselves on this nurse log. The perhumid climate of temperate rainforest environments favors the development of nurse logs like this one in the Joyce Kilmer Memorial Forest.



Plate 5

Stilted Tree

A yellow birch (*Betula allegheniensis*) in the Joyce Kilmer Memorial Forest exhibits stilted roots typical of a mature tree that originally sprouted on a nurse log. The stilted roots grew around the nurse log before penetrating into the mineral soil at ground level. Over the years the nurse log has completely decomposed leaving a cavity between the stilted roots above ground. The moist conditions of the temperate rainforest environment often result in the development of stilted trees.

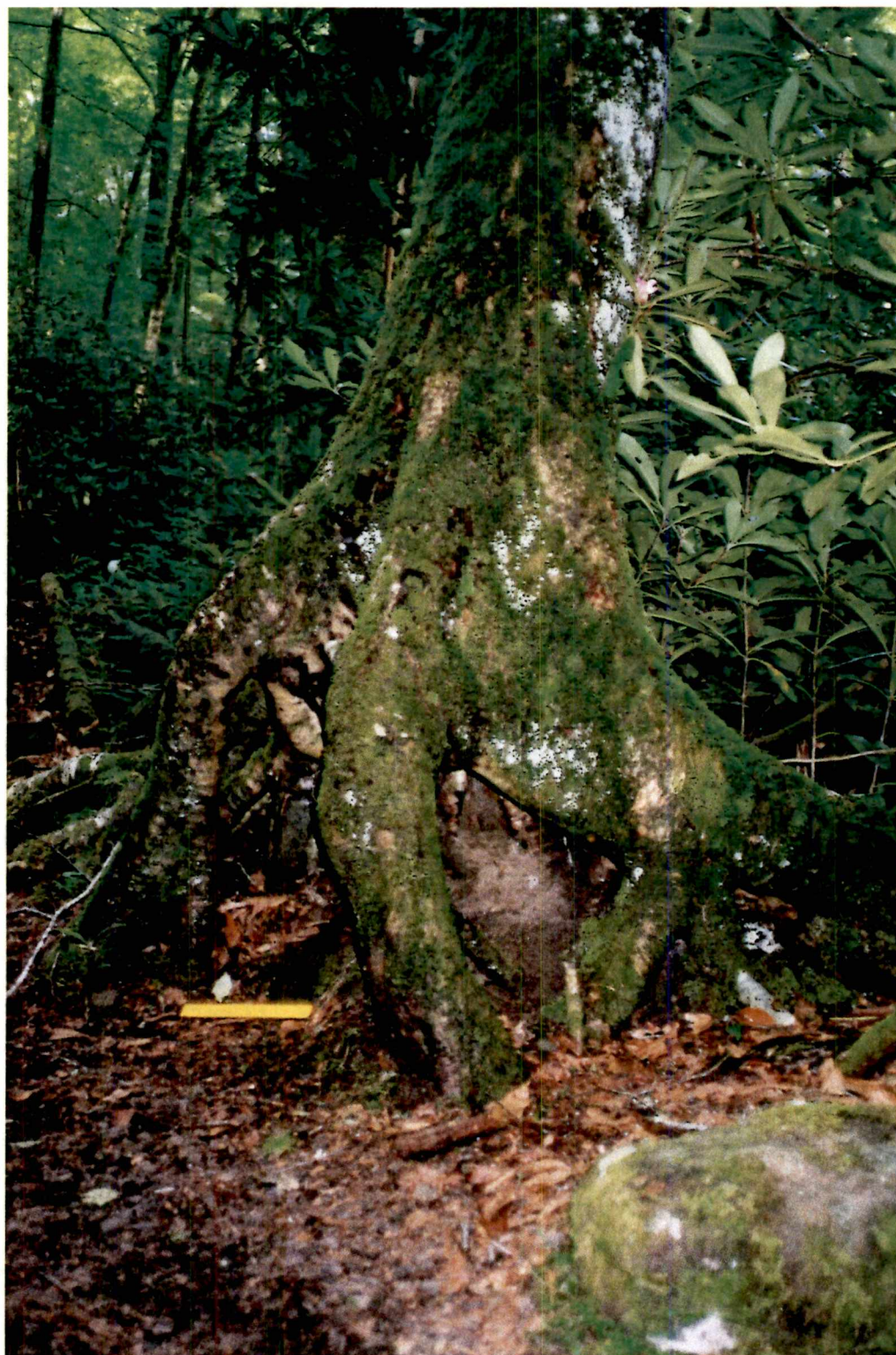


Plate 6

Raw TM image , Bands 1, 6, and 7

In this raw TM image of the local study area, the red, green, blue (RGB) color assignment corresponds to Bands 1, 6, and 7 respectively. With this color assignment, clouds appear yellow and green, vegetation appears violet to blue, and open agricultural and urban areas appear pale blue to nearly white. Even before digital image processing has been performed on these three bands, one can clearly distinguish between the yellow clouds and the pale bluish white urban areas that would normally appear as a similar white color in an image with only the visible light TM Bands.

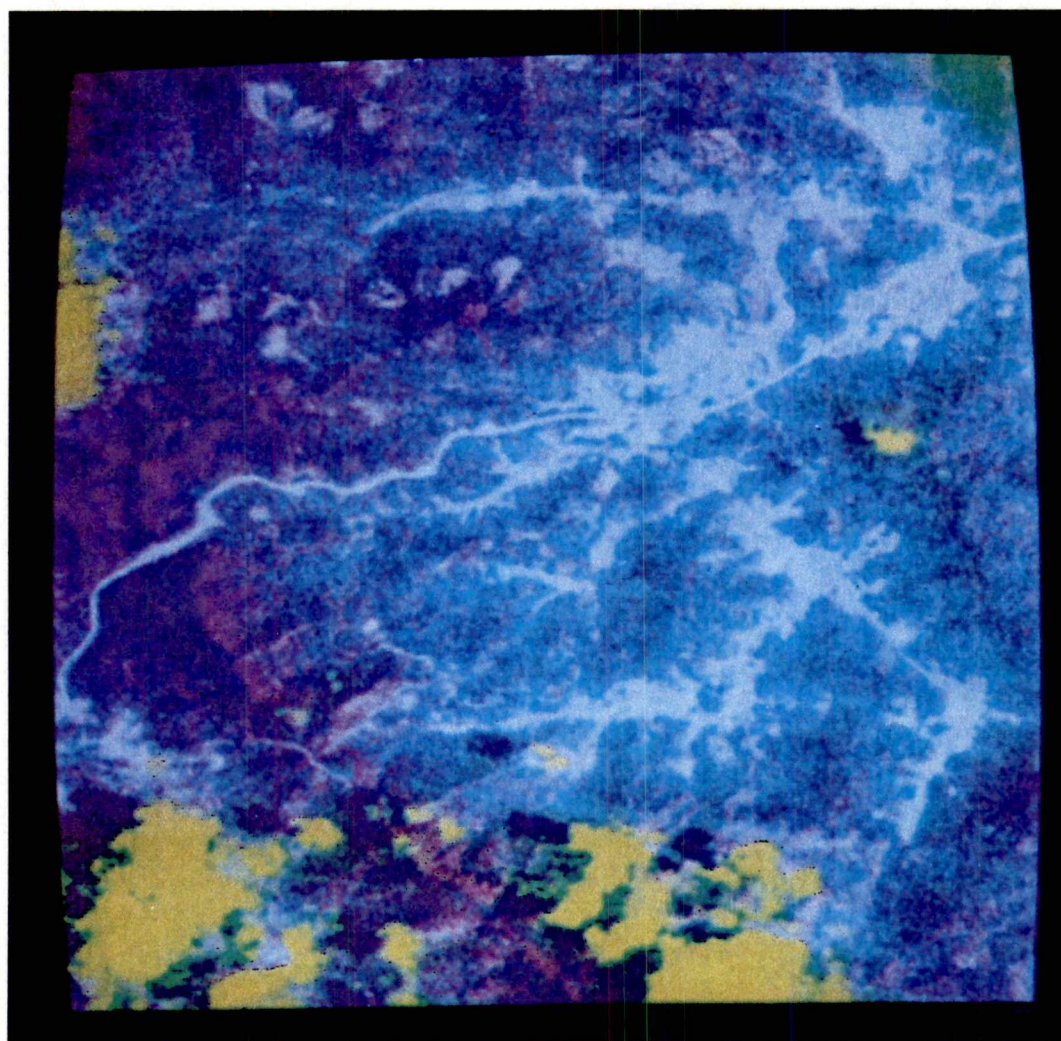
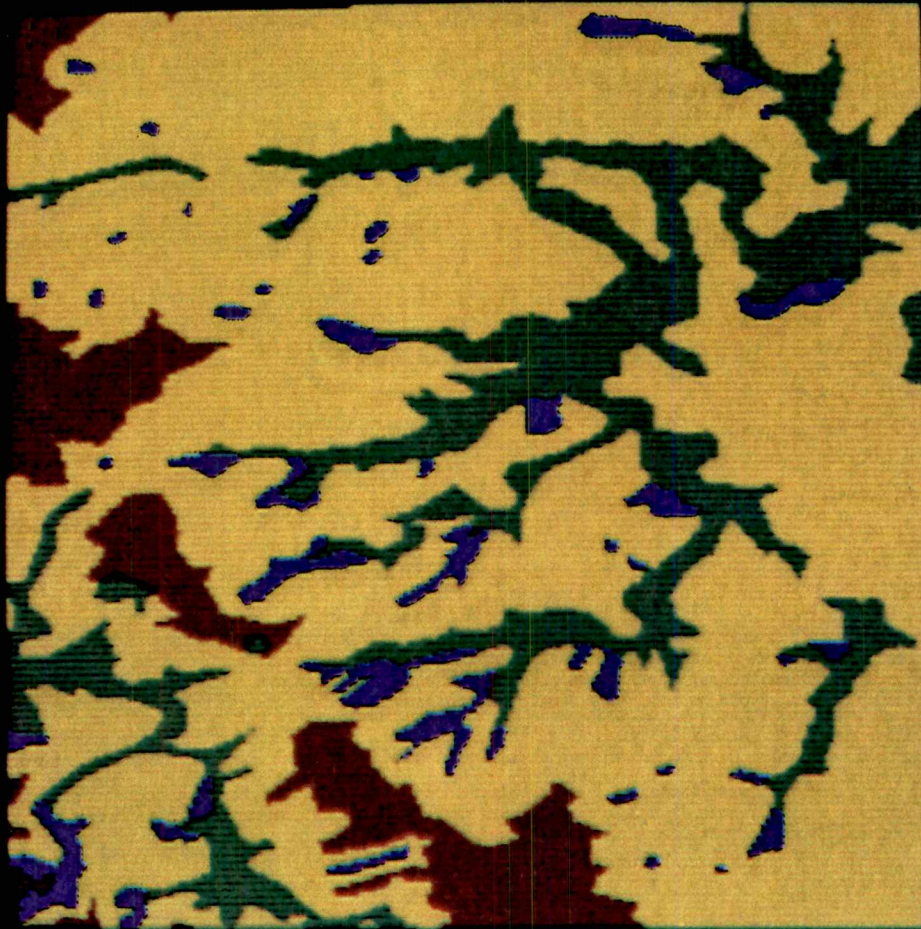


Plate 7

Topographic Classes

The topographic classes for the local study area were manually-derived from USGS 1:24,000 scale topographic maps. The slopes and the coves and valley classes (blue and green) are topographically favorable as potential temperate rainforest environments. The spatial distribution of these topographic classes shows clear relationships with the drainage system of the local study area.



- Slopes
- Coves & Valleys
- General Terrain
- High Elevation

Plate 8

Forest Land Use

The land use patterns of the local study area are fairly typical of the broader Southern Appalachian region. Forest is the dominant land use, while developed areas in the agriculture, urban, and transportation land use classes dominate the valleys and coves, following the drainage network of the area. Clouds obscure a considerable area, but typically are confined to forested mountainous areas of the local study area.

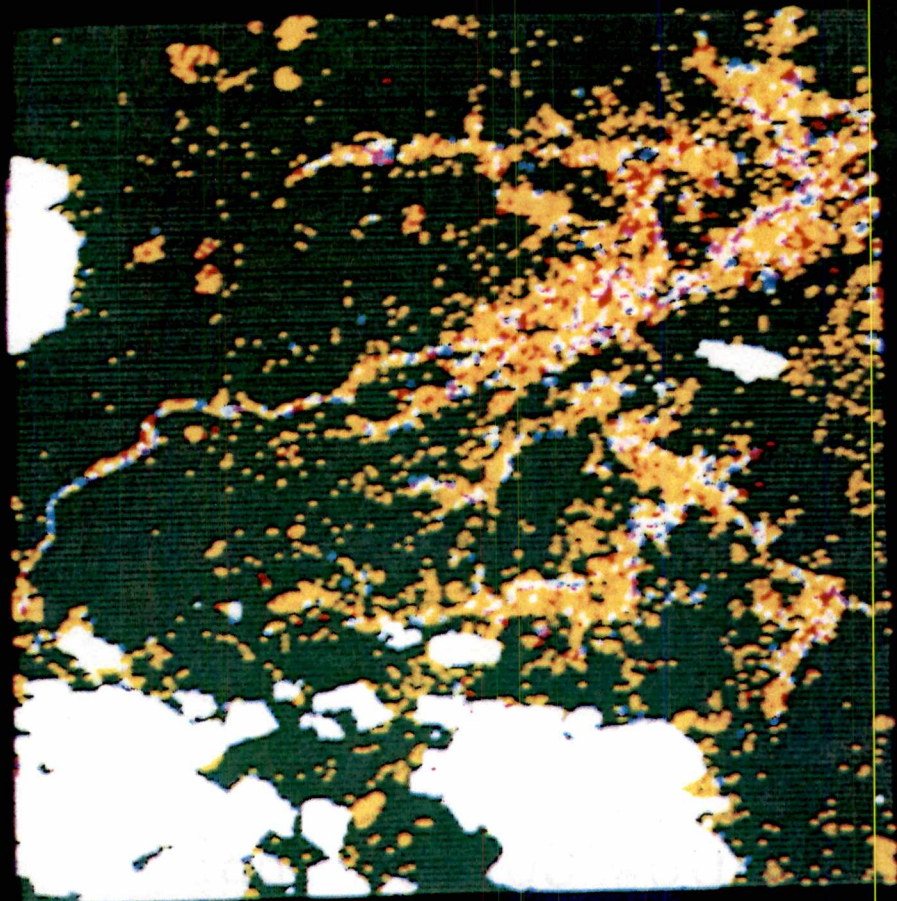
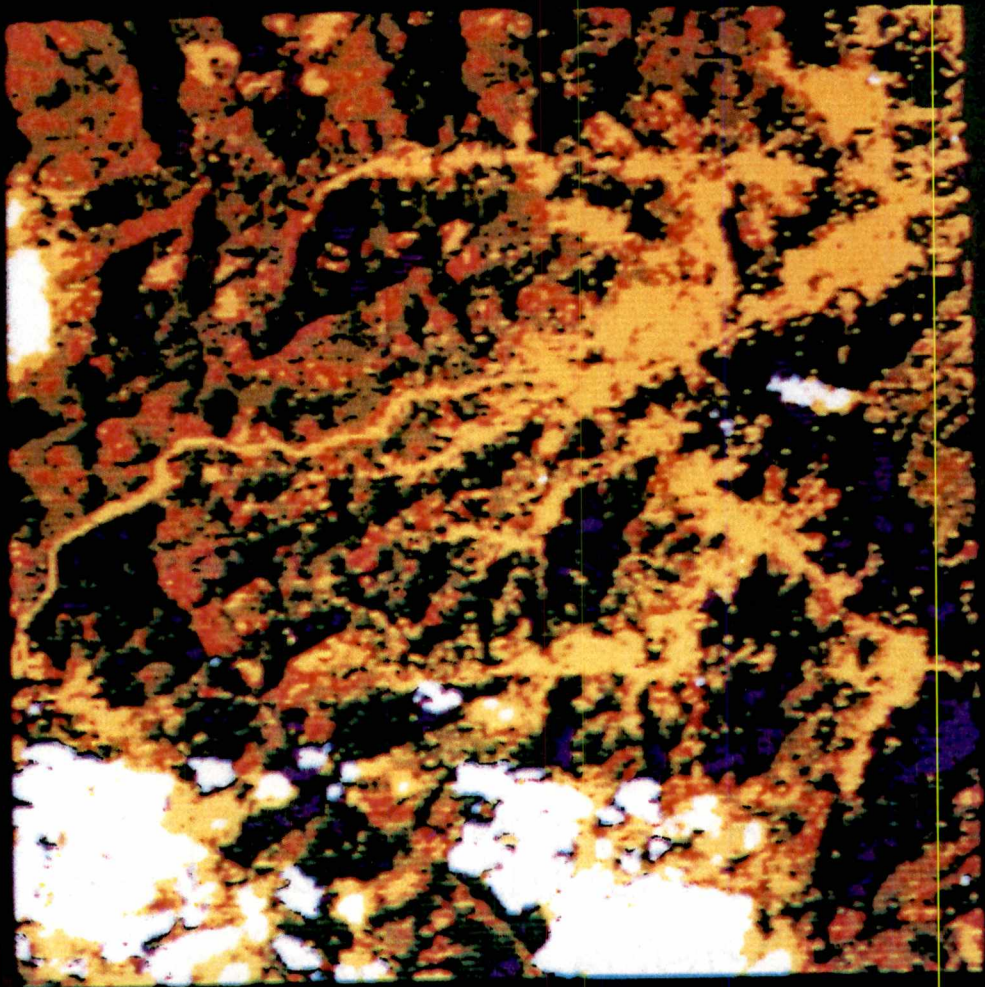


Plate 9

Forest Types

Oak forest (tan) is the dominant forest type in the local study area, often associated with smaller patches of xeric oak forest and mixed oak and pine forest (red). Significant areas of mixed hardwood and hemlock forest and mesic hardwood forest are found near the edge of the cleared coves and valleys (violet and green), as well as on the lower slopes of the ridges. The largest concentration of pine forest (burgundy) is found along the lower ridges in the eastern edge of the local study area.



- Mixed Hardwoods & Hemlock
- Mesic Hardwoods
- Oak Forest
- Pine
- Xeric Oak
- Mixed Oak & Pine
- Non-Forest
- Clouds

APPENDIX B

APPENDIX B

Regression Results

I. Station Elevation to Temperature

Group I

All Stations

(with complete temperature data)

Average Elevation: 1562'

Average Temperature: 56.4° F

Regression Output:

Constant	62.76559
Std Err of Y Est	1.429090
R Squared	0.811291
No. of Observations	53
Degrees of Freedom	51

X Coefficient(s)	-0.00408
Std Err of Coef.	0.000275

Group II

Stations North of 35° 30' Latitude

Average Elevation: 1893'

Average Temperature: 54.5° F

Regression Output:

Constant	61.49710
Std Err of Y Est	1.723910
R Squared	0.676260
No. of Observations	15
Degrees of Freedom	13

X Coefficient(s)	-0.00375
Std Err of Coef.	0.000719

I. Station Elevation to Temperature (Cont.)

Group III

Stations from 35° to 35° 29' Latitude

Average Elevation: 1972

Average Temperature: 54.7° F

Regression Output:

Constant	61.05720
Std Err of Y Est	1.386474
R Squared	0.749199
No. of Observations	17
Degrees of Freedom	15

X Coefficient(s)	-0.00323
Std Err of Coef.	0.000483

Group IV

Stations South of 35° Latitude

Average Elevation: 1030'

Average Temperature 59.1° F

Regression Output:

Constant	63.39861
Std Err of Y Est	0.985881
R Squared	0.736529
No. of Observations	21
Degrees of Freedom	19

X Coefficient(s)	-0.00421
Std Err of Coef.	0.000578

II. Predicted Regression Climate Temperatures
to Predicted Lapse Rate Climate Temperatures

Group I

All Stations

(with complete temperature data)

Regression Sea Level Temperature: 62.8° F

Lapse Rate Sea Level Temperature: 61.8° F

Regression Output:

Constant	-9.3359314286
Std Err of Y Est	0.000000471
R Squared	0.99
No. of Observations	14
Degrees of Freedom	12

X Coefficient(s)	1.165714
Std Err of Coef.	0.000000

Group II

Stations North of 35° 30' Latitude

Regression Sea Level Temperature: 61.5° F

Lapse Rate Sea Level Temperature: 61.1° F

Regression Output:

Constant	-2.6276524433
Std Err of Y Est	0.3517930057
R Squared	0.99
No. of Observations	14
Degrees of Freedom	12

X Coefficient(s)	1.046376
Std Err of Coef.	0.013028

II. Predicted Regression Climate Temperatures
to Predicted Lapse Rate Climate Temperatures (Cont.)

Group III

Stations from 35° to 35° 29' Latitude
Regression Sea Level Temperature: 61.1° F
Lapse rate Sea Level Temperature: 61.5° F

Regression Output:

Constant	5.8294230769
Std Err of Y Est	0.3900595574
R Squared	0.99
No. of Observations	14
Degrees of Freedom	12

X Coefficient(s) 0.894461
Std Err of Coef. 0.014344

Group IV

Stations South of 35° Latitude
Regression Sea Level Temperature: 63.4° F
Lapse rate Sea Level Temperature: 62.7° F

Regression Output:

Constant	-11.969
Std Err of Y Est	0.0000007283
R Squared	0.99
No. of Observations	14
Degrees of Freedom	12

X Coefficient(s) 1.202857
Std Err of Coef. 0.000000

APPENDIX C

Appendix C

Precipitation Efficiency Indices (PEI)

Id#	State	Station	Elevation	Average PEI	1988 PEI
1	NC	ANDREWS	1850	151	108
2	NC	ASHEVILLE WSO AP	2140	100	51
3	NC	ASHEVILLE	2242	78	45
4	NC	BENT CREEK	2110	104	63
5	NC	BLACK MOUNTAIN 2 W	2395	106	64
6	NC	BREVARD	2155	150	90
7	NC	BRIDGEWATER HYDRO	1150	102	50
8	NC	BUCK FOREST	2515	163	115
9	NC	CANTON 1 SW	2662	82	68
10	NC	CATALOOCHEE	2620	97	97
11	NC	CELO 2 S	2700	139	83
12	NC	COWEETA EXP STATION	2249	176	122
13	NC	CULLOWHEE	2192	110	81
14	NC	ENKA	2050	92	48
15	NC	FLETCHER 4 E	2160	104	70
16	NC	FLETCHER 3 W	2070	109	71
17	NC	FOREST CITY 6 SW	985	111	76
18	NC	FRANKLIN	2113	115	88
19	NC	HENDERSONVILLE 1 NE	2160	122	75
20	NC	HICKORY FAA AP	1143	98	72
21	NC	HIGHLANDS	3330	197	184
22	NC	HOT SPRINGS	1332	113	76
23	NC	LAKE LURE 2	1040	104	71
24	NC	LAKE TOXAWAY 2 SW	3080	197	156
25	NC	MARION	1425	115	64
26	NC	MARSHALL	2010	96	59
27	NC	MORGANTON	1160	99	58
28	NC	MURPHY 2 NE	1640	133	106
29	NC	NORTH FORK 2	2480	116	71
30	NC	OCONALUFTEE	2040	156	114
31	NC	PISGAH FOREST 1 N	2110	153	107
32	NC	ROSMAN	2200	198	129
33	NC	SWANNANOA 2 E	2230	132	88
34	NC	TOPOCO	1110	123	97
35	NC	TRYON	1075	126	78
36	NC	WATERVILLE 2	1440	117	80
37	NC	WAYNESVILLE 1 E	2658	102	81
38	GA	BOWMAN	785	92	71
39	GA	CARNESVILLE 4 N	880	152	97
40	GA	CLAYTON 1 SSW	1880	159	104
41	GA	CORNELIA	1470	115	90
42	GA	ELBERTON 2 N	540	110	76
43	GA	HARTWELL	690	101	67
44	GA	LEXINGTON 1 NW	760	95	58

Id#	State	Station	Elevation	Average PEI	1988 PEI
45	GA	LINCOLNTON	480	86	70
46	GA	TOCCOA	1019	119	78
47	GA	WASHINGTON 2 ESE	620	93	75
48	GA	ALPHARETTA 5 SSW	1040	104	77
49	GA	ATHENS WSO AP	802	94	63
50	GA	ATLANTA WSO AP	1010	93	83
51	GA	BALL GROUND	1100	115	85
52	GA	BLAIRSVILLE EXP STN	1917	132	101
53	GA	CANTON	870	115	88
54	GA	CLEVELAND	1570	140	100
55	GA	COMMERCE 4 NNW	750	102	79
56	GA	CUMMING	1320	116	85
57	GA	DAHLONEGA	1430	142	119
58	GA	HELEN	1445	147	119
59	GA	JASPER 1 NNW	1465	120	106
60	GA	MAYSVILLE	920	106	84
61	GA	NORCROSS 4 N	950	103	85
62	GA	U OF GA PLT SCI FM	840	90	67
63	GA	WALESKA	1110	115	104
64	GA	WINDER 1 SSE	960	100	77
65	GA	WOODSTOCK	1055	103	78
66	SC	CEASAR'S HEAD	3100	177	119
67	SC	CLEVELAND 4 S	1070	118	89
68	SC	HOGBACK MOUNTAIN	3230	194	154
69	SC	LONGCREEK	1630	126	93
70	SC	ANDERSON	800	93	69
71	SC	ANDERSON FAA AP	760	96	59
72	SC	CLEMSON UNIVERSITY	819	109	77
73	SC	GAFFNEY 6 E	650	105	65
74	SC	GASTON SHOALS	600	102	67
75	SC	GRNVILLE-SPARTBG WSO	973	104	74
76	SC	LAURENS	589	101	67
77	SC	LOCKHART	400	91	67
78	SC	NINETY NIME ISLANDS	500	108	65
79	SC	OAKWAY 3 WSW	990	95	78
80	SC	PICKENS 5 SE	1140	106	87
81	SC	SALEM 1 SW	980	127	101
82	SC	SANTUCK	520	97	64
83	SC	SPARTANBURG 3 SSE	610	103	66
84	SC	UNION 8 SW	549	109	76
85	SC	WALHALLA	980	105	81
86	SC	WEST PELZER	850	99	72
87	SC	WHITMIRE 4 NE	400	103	72
88	SC	WOODRUFF 5 NW	760	89	67
89	TN	ATHENS	940	107	93
90	TN	CHATTANOOGA WSO AP	692	105	92
91	TN	CONASAUGA 2 N	845	117	84
92	TN	GATLINBURG 2 SW	1454	116	102
93	TN	KNOXVILLE WSO AP	949	102	92

Id#	State	Station	Elevation	Average PEI	1988 PEI
94	TN	NEWPORT 1 NW	1036	115	74
95	TN	SEVIERVILLE 1 SE	930	107	72
96	TN	MT. LECONTE	6493	338	216

VITA

Michael J. Daly is a graduate of Oak Ridge High School, Oak Ridge, Tennessee. After completing study in a California Agricultural Extension Service program, he received a Certificate of Biological Horticulture from the University of California, Santa Cruz in 1980. Later, he completed his Baccalaureate degree at the University of Tennessee, Knoxville with a major in Geography. After the completion of his undergraduate work, he pursued a management career for several years residing for a period in several locations including Athens and Elizabethton, Tennessee and Clifton Forge, Virginia.

In 1990, he returned to the University of Tennessee, Knoxville to pursue a Master degree in Geography. During this time, he taught introductory physical and human geography courses in the Geography Department. He also did database development work for the Oak Ridge National Laboratory. Currently, he is working in the UT Management Science Department on a GIS-based Biomass Resource Assessment System.

His outside interests center on Aquatics. He is a member of the Knoxville Masters Swimming Club and the UT Water Polo Club. He has actively participated in fund-raising activities for the American Red Cross, as well as volunteering as a teacher for the Red Cross Learn to Swim program at the Inskip pool during the past two summers.