

# Testing Ecoregions in Kentucky and Tennessee with Satellite Imagery and Forest Inventory Data

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**Abstract:** *Ecoregions are large mapped areas of hypothesized ecological uniformity that are delineated subjectively based on multiple physical and biological components. Ecoregion maps are seldom evaluated because suitable data sets are often lacking. Landsat imagery is a readily available, low-cost source of archived data that can be used to calculate the normalized difference vegetation index (NDVI), which is associated with seasonal and annual vegetation conditions. This paper reports on a study designed to test the use of NDVI as an integrating variable for detecting differences among mapped ecoregions and determine if NDVI was associated with biological components within ecoregions using USDA Forest Service Forest Inventory and Analysis (FIA) field data. Published 1.1 km resolution georeferenced NDVI imagery was obtained at the beginning (June 22) and end (September 23) of the summer growing season for 11 years (1989-1999). Public domain GIS software (WinDisp4) was used to determine NDVI values at 5,399 georeferenced, forested plot locations in Kentucky and Tennessee that are periodically inventoried by FIA. Plots were grouped by ecoregions of various scale and tested for significant differences. Analysis of variance revealed significant ( $P < 0.001$ ) differences in mean NDVI between the two macro-scale ecoregions (divisions) and among most of the next lower ecological units (provinces). Regression analysis indicated that NDVI was associated ( $P < 0.01$ ) with season of sampling, elevation, and forest stand basal area of the inventory plots. At the ecoregion analysis scale, NDVI values consistently increased with higher elevation and forest basal area at the plot locations. We concluded that NDVI determined at FIA plot locations has potential for testing differences among ecoregions. Satellite imagery has often been used to determine classification accuracy within small mapped ecosystems; results from our study suggest that imagery may also be used to test for hypothesized overall differences between large mapped ecosystems.*

**Keywords:** AVHRR, ecoregionalization, NDVI, Palmer drought severity index, remote sensing.

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## Introduction

Ecoregions are "any large portion of the Earth's surface over which the ecosystems have characteristics in common" (Bailey 1998). When mapped, they can be considered as hypotheses for testing and refinement (Rowe and Sheard 1981). Ecoregionalization is the process of knowledgeable integration of spatial environmental physical factors to form regions of hypothesized ecological uniqueness (Bailey 1998). Recently, this process has been used by conservation and land-management agencies in the planning, analysis, and assessment of resource-related issues (Griffith and others 1999). Maps of ecoregions have been produced by state (Homoya and others 1985, Hargrave 1993) and federal (Keys and others 1995, Griffith and others 1997) agencies, and by conservation organizations (The Nature Conservancy 2001). Ecoregional delineations have been used for many purposes, including development of forest growth models (Huang 1999) and ecosystem-based management plans (Haynes and others 1998), selection of research areas (Snyder and others 1999), assessment of forest resources (Rudis 1999), and analysis of water quality (Griffith and others 1999). Although questions have been raised about the appropriateness of ecoregional delineations for these purposes (Wright and others 1998), little attention has been given to validation of them (Rowe and Sheard 1981, Bailey 1984, Omernik 1995, Smith and Carpenter 1996, Brown and others 1998).

Validation of ecoregional delineations differs in several important ways from the process of testing conventional classifications such as soil maps or maps of vegetation cover types (Edwards and others 1998). First, the "real" taxonomic identities of ecological units on many maps are often unknown because these units are characterized subjectively by consensus during delineation and review. However, objective, quantitative methods have been investigated (Host and others 1996, Hargrove and Hoffman 1999) and criticized as inefficient (Rowe and Sheard 1981). Second, ecoregional delineations are generalizations and syntheses of many environmental components (Bailey 1998) and are not delineated for a specific purpose that provides a convenient basis for testing. Finally, and perhaps most importantly, obtaining a suitable dataset for an appropriate response factor is difficult and costly because ecoregions extend over large areas ranging from hundreds of thousands to millions of km<sup>2</sup> (Bailey 1984). Vegetation is typically used as a response variable for testing ecoregional delineations (Bailey 1984, Edwards and others 1998, Schreuder and others 1999), and water quality has been employed in this way (Bailey 1984). Remote sensing is an economical means of acquiring data bases and satisfies some of the identified problems of testing and validation of ecoregional delineations (Loveland and others 1991, Brown and others 1998).

Remote sensing has often been used to develop classifications of vegetation types, but has seldom been employed to test for differences between hypothesized ecosystems. Ramsey and others (1995) found that normalized difference vegetation index (NDVI) was associated significantly with five ecoregions in

Utah mapped by Omernik (1987), each of which occupied a distinct elevation zone and was dominated by a characteristic type and abundance of xerophytic vegetation. The NDVI, a ratio of the red and near-infrared spectral bands, is correlated with the amount of actively photosynthesizing biomass. Since being devised in the 1970s, the use of NDVI has largely dominated vegetation analysis by remote sensing (Loveland and others 1991), although a number of other indices have been evaluated (Gutman 1991). NDVI has been associated with a number of climatic and vegetation parameters, including drought (Singh and others 2003), wildland fire risk (Maselli and others 2003), land degradation (Wessels and others 2004), forage production (Hill and others 2004), leaf area index (Wang and others 2005), stand age and density (Sivanpillai and others 2006), continental-scale vegetation type classification (Loveland and others 1995), and net primary production (Handcock 2000, Meng and others 2007). It is reasonable to think that NDVI data obtained by remote sensing could be used to test for vegetational differences among ecoregions.

Forest Inventory and Analysis (FIA) plot data constitutes another data base that has characteristics desirable for use in the validation of ecoregional delineations. Schroeder and others (1997) found that FIA plots provided suitable data for regional estimates of biomass production. Schreuder and others (1999) reported that inventory data provides a suitable basis for a system of forest monitoring. Plot and tree level data are readily available for inventory plots, field locations are known with reasonably acceptable accuracy, and the network covers a broad geographic area (Hansen and others 1992).

Testing of ecoregional delineations by means of remote sensing has not been reported for the eastern U.S. The eastern U.S. has more precipitation, less topographic relief, and less contrast between forest cover types than the western landscape studied by Ramsey and others (1995). We think it probable that remotely sensed NDVI integrates the quantity, composition, and condition of vegetation in eastern forests in response to environmental relationships as it does in Utah. Effects of exposed soil on NDVI (Huete 1988) should be considerably less in the eastern U.S. because canopy cover is almost complete over forested sites. This paper reports on a study designed to test the use of NDVI as an integrating variable for detecting differences among mapped ecoregions in the relatively humid eastern U.S. We addressed two questions: (1) Does mean NDVI vary among ecoregions within a hierarchical framework of ecological units and (2) How does NDVI vary in relation to environmental and biological factors? We used software, data sets, and techniques that would be readily available to ecological researchers having an understanding of remote sensing but who lack extensive technical training in the discipline.

## Materials and Methods

### NDVI Data

Imagery, which originated from the AVHRR (advanced very high resolution radiometer) sensor on the NOAA-11 satellite, is retrieved daily and processed by the U.S. Geological Survey (Loveland and others 1991, Burgan and Hartford 1993). The 1.1 km resolution imagery was georeferenced and made into weekly or biweekly composite images of generally cloud-free data bases of several spectral wavelength bands (Holben 1986). Data from two of the five spectral channels are used for calculation of NDVI:

$$\text{NDVI} = (\text{Channel 2} - \text{Channel 1}) / (\text{Channel 2} + \text{Channel 1})$$

where Channel 1 is the red, visible portion of the electromagnetic spectrum (0.58 to 0.68 microns) and Channel 2 is the infrared portion of the electromagnetic spectrum (0.725 to 1.10 microns). The underlying premise of the NDVI is that incoming radiation in the visible spectrum (0.58-0.68) is absorbed by chlorophyll in vegetation and that infrared wavelengths are reflected. Thus, NDVI is directly correlated with the quantity of green, photosynthesizing vegetation. Values of NDVI, which can range from -1.0 to 1.0, were recoded from 0 to 255. Values < 100 indicate the presence of clouds, snow, bare soil (i.e. fallow agricultural fields), and land surfaces naturally lacking vegetation. Values  $\geq 100$  indicate the presence of varying quantities of photosynthesizing vegetation biomass. Water bodies were coded as 255. We used 11 years (1989 - 1999) of stock, "off-the-shelf," NDVI imagery that had been retrieved from the EROS data center by the USDA Forest Service and published as annual archives primarily for use in fire danger rating (Burgan and Chase 1997a-1997h, Burgan and Chase 1998, Burgan and others 1999, USDA Forest Service 2000). The georeferenced imagery consisted of weekly or biweekly composites of cloud-free pixels of the highest NDVI value. None of the NDVI imagery had been corrected for atmospheric effects (Song and others 2001). We used public domain image display and analysis software, WinDisp4 (FAO 1999), to extract and merge blocks of NDVI images from the data sources and to determine median NDVI within ecoregions. Because our analysis did not involve classification, change detection, time series analysis, or other highly specialized use of imagery, we did not consider that data manipulation or transformation, such as tasseled cap or Fourier, was necessary to achieve our objectives.

### Area Studied

**Vegetation:** We utilized data for ecoregions within the southeastern portion of the upland oak-hickory (*Quercus-Carya*) forest type of the Eastern U.S., also known as the Central Hardwood region (Braun 1950). This is the most extensive forest type of the conterminous U.S., occupying about 46 million ha (Burns 1983). The oak-hickory type occurs in the east-central U.S., from the prairie

borders in Texas northward to the Dakotas and eastward to the Appalachian Mountains from Georgia to southern New England. It is most extensive in Kentucky, Tennessee, and the Ozark and Ouachita Highlands. The type is characterized by deciduous hardwoods that form a nearly closed canopy consisting of four or more layers on mesic sites: a tall (25-30 m) tree overstory, an open midstory of immature canopy and shade-tolerant tree species, a low (1-5 m) shrub layer of ericaceous species, and an herb layer. Northern red oak (*Q. rubra* L.), black oak (*Q. velutina* Lam.), and white oak (*Q. alba* L.) occur throughout the range of the type; other species of local importance include chestnut oak (*Q. prinus* L.), post oak (*Q. stellata* Wengen.), and scarlet oak (*Q. coccinea* Muenchh.). Hickory species include pignut (*C. glabra* (Mill.) Sweet) and mockernut (*C. tomentosa* (Poir)Nutt.). Species in the midstory include sourwood (*Oxydendrum arboreum* (L.) DC.), eastern redbud (*Cercis canadensis* L.), and flowering dogwood (*Cornus florida* L.). The shrub layer consists of rosebay rhododendron (*Rhododendron maximum* L.) and mountain laurel (*Kalmia latifolia* L.). The oak-hickory type predominates on almost all landscape positions throughout its range. In mountainous areas, however, lower slopes and coves often have a greater proportion of mesophytic species, including yellow-poplar (*Liriodendron tulipifera* L.) and red maple (*Acer rubrum* L.). The type grades into northern hardwoods in the higher elevation and northern parts of its range and the oak-pine type in its southern range.

Climatic regime of the oak-hickory region is humid continental with generally short, cool winters and long, warm summers (Burns 1983). In the central part of the area occupied by the type, mean daily temperature averages about 12.8 °C and the frost-free period is around 180 days. Annual precipitation in the central part averages from 75 to 100 cm, about half of which occurs during the growing season. Periods of moisture deficit lasting from 2 to 6 weeks are common during the late summer. Annual snowfall averages about 25 cm.

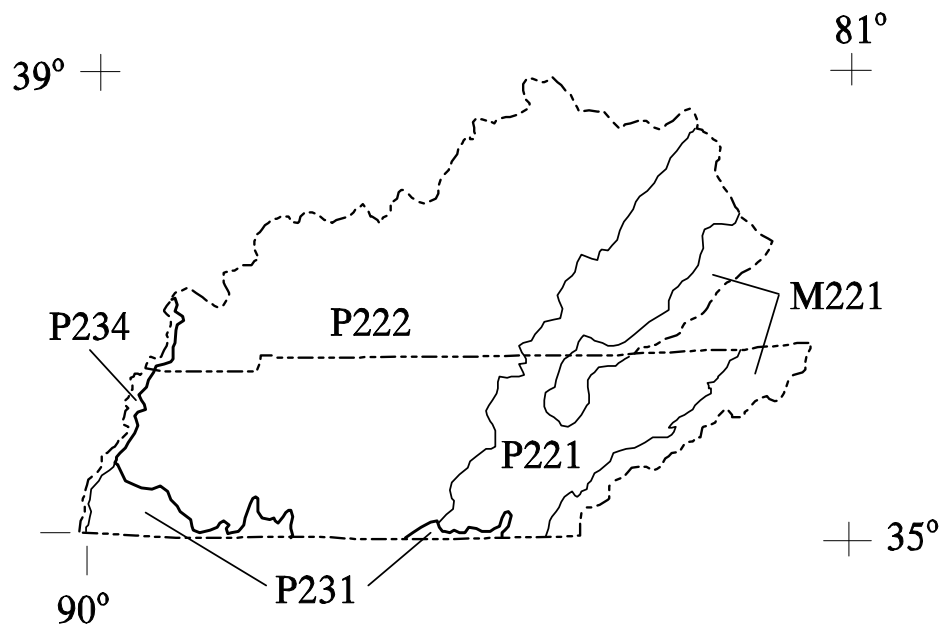
The topography of the area consists mostly of low, open hills, although areas of steep relief occur in the Appalachian, Cumberland, and Ozark Mountains. The oak-hickory type is restricted to elevations below about 1,650 m on exposed slopes and ridges in the Southern Appalachians. Geologic parent material consists mostly of glacial material, residual sandstone, shales, and limestone, although gneisses and schists also occur. Soils range from cool-moist Spodosols to warm-dry Alfisols.

The data utilized in our study are for the central portion of the oak-hickory type in Kentucky and Tennessee, an area of about 213,000 km<sup>2</sup>. The oak-hickory type in these states consists of areas where the plurality of tree species are upland oaks or hickory, and where associated species include yellow-poplar, elm (*Ulmus* L spp.), maple, and black walnut (*Juglans nigra* L.).

**Ecoregions:** This area includes ecoregions delineated at the upper three levels (i.e. domain, division, province) of the USDA Forest Service hierarchical

framework of ecological units (Cleland and others 1997) (figure 1). In this framework, domains occupy millions of hectares, divisions within a domain occupy hundreds of thousands of hectares, and provinces in a division occupy tens of thousands of hectares. Ecoregion delineation and nomenclature follow Keys and others (1995).

The Humid Temperate Domain, 200, includes all of the study area. This domain is characterized by sufficient precipitation to support forests of broadleaf deciduous and needleleaf evergreen trees, which constitute the dominant vegetation. This domain is subdivided into divisions based on characteristics of the climate during the winter (Bailey 1995). The study area contains two divisions: 220 and 230. Divisions delineate major changes in temperature regimes (Bailey 1995) and tend to be oriented in an east-west direction. The Hot Continental Division, 220, delineates an area of hot summers and cool winters and supports winter deciduous forest vegetation characterized by tall broadleaf trees. The climate of the Subtropical Division, 230, which lies south of 220, is characterized by lack of cold winters and by high humidity during the summer and also by a higher proportion of conifers (primarily *Pinus L.spp.*) in the forest vegetation. The dividing line between the 220 and 230 divisions represents an isotherm of about 22 °C for the warmest month. Most of the study area consists of division 220, which includes three provinces.



**Figure 1:** Ecoregions at the domain, division, and province hierarchical levels in the study area, which consisted of the states of Kentucky and Tennessee. Only ecoregions at the province level are identified. In the hierarchical structure of the Forest Service classification framework (Cleland and others 1997), domain 200 and divisions 220 and 230 are implicitly represented by the taxonomic structure of the numbering system. Thus, the entire area is contained in domain 200 and the wide boundary line along the southern and western parts of Tennessee separates divisions 220 and 230.

Provinces are components of a division that correspond to broad vegetation regions, and that conform to climatic sub-zones controlled primarily by continental weather characteristics such as length of dry season and duration of cold temperatures (Bailey 1995). Provinces are also characterized by similar soil orders and potential natural vegetation. Five provinces are represented in the study area, one mountainous (M221) and four with planar or plateau-type surfaces (P221, P222, P231, and P234).

Province M221 extends across the western slope of the Appalachian Mountains in Tennessee and includes a small part of the Cumberland Mountains in Kentucky. A landscape of high relief is characteristic of this province. Geologic formations generally consist of Precambrian metamorphosed gneisses and schists, although the Cumberland Mountains were formed by differential erosion of level-bedded sandstones. Vegetation is dominated by species of *Quercus*, although mesophytic species predominate in mountain valleys. Annual precipitation is greater here than in other provinces, primarily as a result of orographic effects. Nine percent of the study area is contained in M221. Except for the heavily populated broad intermountain basins, most of the province is forested, particularly the steep, mountainous slopes.

Province P221, Eastern Broadleaf Forest (Oceanic), is in the eastern part of the study area and makes up about 22 percent of the study area. Precipitation here is less than in M221, but greater than in the adjacent province to the west. Geology is variable, ranging from level-bedded sandstones on the Cumberland Plateau to the carbonate rocks of the Ridge and Valley geologic province. Parts of P221 have been weathered and dissected to present mountainous terrain. Altitude ranges from about 200 to 800 m. Vegetation consists of arborescent species dominated by oaks. Forests have been cleared from 30 to 40 percent of the land area for urban, pasture, and agricultural land uses.

Province 222, Eastern Broadleaf Forest (Continental), is the largest of the ecoregions under consideration, occupying 63 percent of the study area. Its geology consists of Paleozoic level-bedded sandstones and siltstones that have weathered to form topography of low, rolling hills and dissected plateaus. Vegetation is dominated by oaks and hickories. Forest cover ranges from about 45 percent in the eastern and central part of this province to 70 percent in the west.

A small part of P231 (Southeastern Mixed Forest) occurs along the southern boundary of Tennessee, and constitutes 4 percent of the study area. Geologic formations are irregularly bedded Quaternary and Cenozoic sands and clays. Forest canopy vegetation consists mostly of oaks and hickories; pines (*Pinus* L.spp.) are more prevalent here than in neighboring provinces. Land use is mostly forestry and agriculture.

Province 234 (Lower Mississippi Riverine Forest), the smallest of the five ecoregions included in the study (2 percent of the study area), borders the

Mississippi River and is characterized by flat, alluvial plains that are flooded periodically. Areas of late Pleistocene, wind-deposited loess occur and form a distinctive boundary with P222. A large portion of this province was formerly utilized for agricultural purposes, particularly areas that had more favorable soil moisture relations, but reforestation is now occurring (Schweitzer and Stanturf 1997). Forest vegetation includes a number of mesophytic species that can withstand periodic flooding, such as water tupelo (*Nyssa aquatica* L.), blackgum (*N. sylvatica* Marsh.), sweetgum (*Liquidambar styraciflua* L.), some oaks, and baldcypress (*Taxodium distichum* (L.) Rich.). The physical characteristics and vegetation of P234 are quite distinct from those of the other provinces.

In summary, the natural vegetation of the ecoregions studied consists primarily of forests with an upper and mid-canopy cover of arborescent species dominated by oaks. Divisions are most clearly distinguished by physiography and differences in vegetative composition. Vegetational differences among provinces within a division are less distinct. Bailey (1995), Griffith and others (1997), and Delcourt and Delcourt (2000) provide more information on ecological relationships in the study area. Ecoregions delineated at the division and province scales, unlike ecological units at lower hierarchical levels, are not repeated across the landscape. Approximately half of the two-state study area is forested.

## Experimental Design

We designed our study with the assumption that the ecoregion (e.g. division, province) is the experimental unit, or the smallest portion of the study that receives a treatment. Treatments are the environmental conditions and biological processes used to define each ecoregion. Treatments are defined by physical factors -- climate (e.g. temperature, precipitation), geology, landform, and soils. Forest vegetation is the relatively stable biological characteristic that responds to the physical environmental treatment. NDVI was employed to quantify the biological response. The environmental treatment of each ecoregion was assumed to be a random effect.

Climate varies both with location within the study area and over time. Therefore, because NDVI quantifies the phenological state of vegetation, which we hypothesize varies among ecoregions as a function of climate, it was measured at two fixed times during the growing season.

Replication of the experimental units for statistical testing is problematic because ecoregions at the division and province hierarchical levels are unique and thus do not repeat across the landscape. We used years as replications and considered their effects to be random. Experimental error for testing treatments consisted of unexplained variation in NDVI resulting from phenological differences in vegetation at the measurement dates, unmeasured atmospheric conditions, and other variation that was not accounted for by treatments.



## **Ecoregion Analyses**

The population of NDVI values within each ecoregion was sampled as values for the areas around the FIA inventory plot locations (Hansen and others 1992). The FIA plots were utilized to identify forested sample sites for determination of NDVI and to exclude landcover associated with nonforest uses (e.g. metropolitan, agricultural). A total of 5,399 forested plots were available for which the geographic coordinates had been determined to the nearest 100 seconds of latitude and longitude. One hundred seconds of latitude equals approximately 1.6 km. The median of nine NDVI values was determined from a 3x3 grid (3.3 x 3.3 km) centered at each FIA inventory plot to ensure inclusion of the plot in the sample area.

We determined NDVI at the FIA plot locations for 11 years. Each year, NDVI was sampled at the summer solstice (June 22) and the fall equinox (September 22). In the study area, these dates generally correspond to full expansion of foliage at the highest altitudes in late spring and also before initiation of leaf abscission, near the end of the growing season. In addition, the June date is representative of the annual period before soil moisture generally becomes limiting, and September is the period when moisture deficits may become maximized. The Palmer drought severity index (PDSI) was used to account for variation in annual and seasonal NDVI associated with meteorological drought (Palmer 1965). Published values of PDSI that had been calculated for each of the four climatic divisions in each state were used in the analysis.

We used analysis of variance to determine if variation in the response variable (NDVI) was affected by differing treatments, which were represented by ecoregions. We restricted tests of significance to ecoregions within the hierarchical structure of the classification. For example, we first used all data to compare divisions, and then conducted separate analyses of provinces within each division (i.e. two data sets were formed by subsetting on division). Orthogonal contrast tests were used to determine all differences among divisions and provinces.

## **NDVI Modeling**

We used multiple regression on the linked FIA and NDVI data bases to investigate the effects of selected topographic, geographic, and vegetational variables on NDVI. We followed Hansen and others (1992) in selecting altitude and stand basal area as vegetational and topographic variables to characterize each inventory plot. Plot latitude and longitude were included as surrogate variables to account for variation in climate associated with geographic location within ecoregions. The response variable was NDVI averaged by season over the 11 years studied. Other variables in the FIA data set (i.e. aspect and slope gradient) were excluded from analysis because of the broad area represented by each sample plot (10.1 km<sup>2</sup>).

## Results

### Inventory Plot Characteristics

A total of 5,399 FIA inventory plots (3,049 in Kentucky and 2,350 in Tennessee) were used in the analysis (table 1). Plots were well distributed throughout each ecoregion. Mean topographic elevations were greatest (563 m) in M221, the mountainous province, and least (90 m) in P234, near the Mississippi River. Elevations in P222 and P231 were similar, but variation was greater in P231. Stand basal area was about 2.8 m<sup>2</sup>/ha higher for division 230 than for division 220. Among provinces, stand basal area was greatest (20.3 m<sup>2</sup>/ha) in M221 and least (13.2 m<sup>2</sup>/ha) in P222.

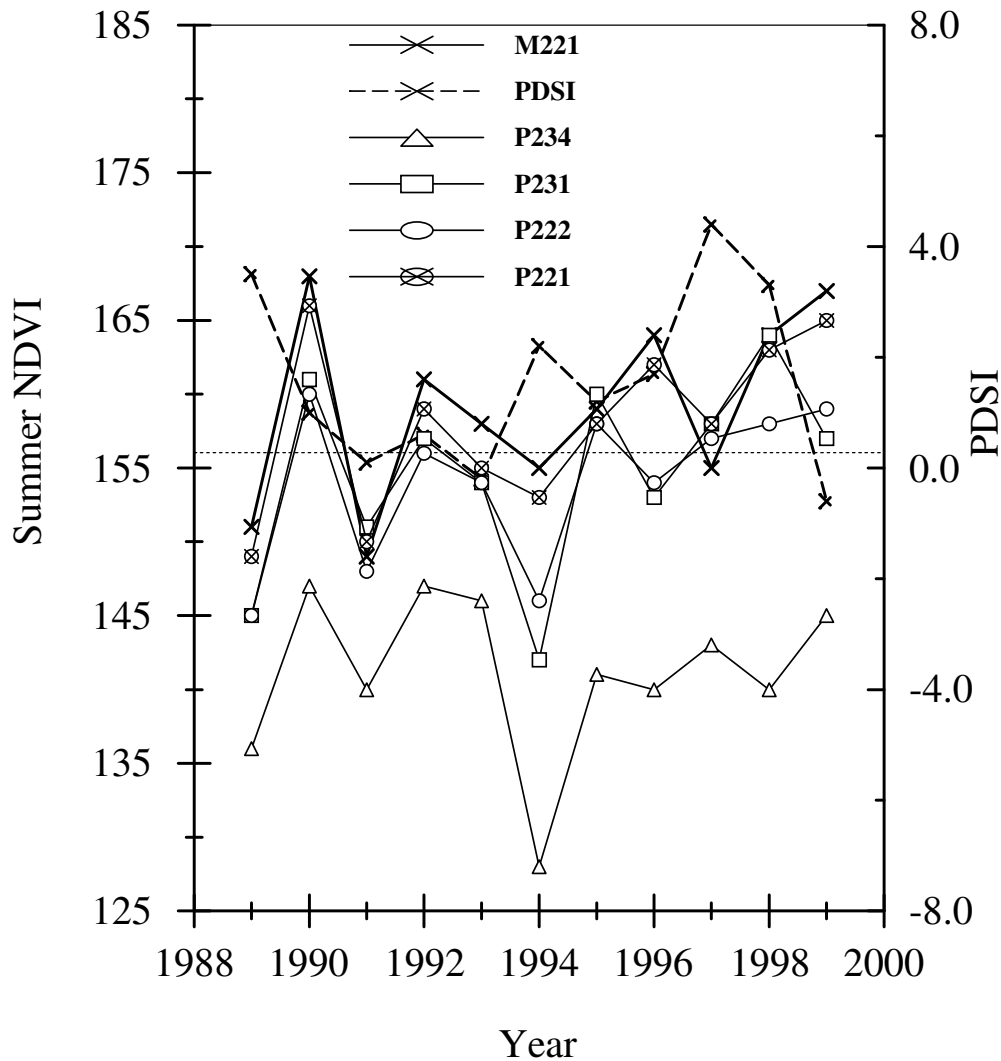
### NDVI and Ecoregions

Mean summer (June) NDVI averaged 155.8 among provinces for the 11-year period studied (figure 2). The range in average summer NDVI across all ecoregions varied from about 167 in 1990 to 127 in 1994. M221 had the highest summer NDVI in most years, and P234 had the lowest summer NDVI every year. Annual direction and magnitude of change in NDVI was generally consistent among provinces for most years of the study, although there were notable exceptions in 1996 and 1997. The mean summer PDSI averaged across all provinces ranged from -0.6 to 4.4 during the study period. The PDSI pattern agreed with the pattern of NDVI for about half of the years, but differed visibly for other years (e.g. 1989, 1994, and 1997).

Ecoregions accounted for highly significant differences in average NDVI between divisions and provinces within divisions for the summer growing season (table 2). Similar patterns were apparent in the fall (September) data, but the relationships were not as strong. The multiple coefficient of determination ( $R^2$ ) values of the analyses of variance for the summer and fall seasons were  $R^2 =$

**Table 1:** Mean ( $\pm$ SD) topographic, geographic, and vegetation characteristics of forest inventory and analysis sample plots by ecoregion hierarchical level.

Ecoregion	Plots	Elevation	Latitude	Longitude	Basal area
	number	meters	----- degrees -----		m <sup>2</sup> /ha
Domain 200	5399	299(161)	36.8(1.0)	85.5(1.9)	15.7(10.7)
Divisions in domain 200					
220	5222	302(161)	36.8(0.9)	85.4(1.8)	15.6(10.8)
230	177	195(123)	35.3(0.5)	88.4(1.4)	18.4(8.4)
Provinces in division 220					
M221	624	563(212)	36.4(0.7)	83.2(0.9)	20.3(10.0)
P221	1479	380(105)	36.7(0.9)	84.0(0.9)	18.6(9.7)
P222	3119	214(70)	36.9(1.0)	86.4(1.5)	13.2(10.8)
Provinces in division 230					
P231	145	217(124)	35.1(0.1)	88.1(1.4)	18.8(7.2)
P234	32	90(17)	36.3(0.6)	89.4(0.3)	16.5(12.3)



**Figure 2:** Mean normalized difference vegetation index (NDVI) and regional Palmer drought severity index (PDSI) at the summer solstice (June 22) by ecological province over the 11 years of the study. The long-term (11 years) mean summer NDVI is indicated by the horizontal dashed line.

0.9068 and  $R^2 = 0.7436$  respectively. The mean summer division-to-division difference was approximately 10 NDVI units, which was significant at the  $P < 0.0001$  level. The three provinces in division 220 were M221, P221, and P222. Mean summer NDVI of M221 did not differ from that of P221 ( $P = 0.1560$ ). However, NDVI of P222 was significantly different from that of M221 ( $P < 0.001$ ) and that of P221 ( $P = 0.002$ ). The two provinces in division 230 were P231 and P234. Mean summer NDVI of P231 (154.7) was significantly different ( $P < 0.0001$ ) from that of P234 (141.1). NDVI for P231 and NDVI for P234 were not significantly different ( $P = 0.7511$ ) for the fall season.

Inclusion of PDSI as a covariable in the analysis of variance for the summer season explained a small but significant ( $P = 0.0032$ ) portion of the variation in

**Table 2:** Seasonal mean ( $\pm$ SD) NDVI and orthogonal contrasts among hierarchical ecoregions. <sup>1</sup>

<b>Ecoregion</b>	<b>Summer (June 21)</b>	<b>Fall (September 21)</b>
Divisions in domain 200		
220	157.2(6.1)a	153.8(6.2)a
230	147.0(9.2)b	151.6(5.6)b
Provinces in division 220		
M221	159.4(6.4)a	155.6(7.3)a
P221	158.1(5.7)a	153.8(6.1)ab
P222	154.1(5.4)b	151.9(4.8)b
Provinces in division 230		
P231	154.7(6.7)a	151.8(6.1)a
P234	141.1(5.6)b	151.3(5.3)a

<sup>1</sup>Within hierarchical ecoregion groups, means followed by the same letter are not significantly different ( $P < 0.001$ ).

mean NDVI within and between provinces. The coefficient for PDSI was 1.9998, and the value of  $R^2$  increased from 0.907 to 0.926. PDSI was not significant ( $P = 0.1689$ ) when included as a covariable in an analysis of variance model for fall NDVI, and had a coefficient of -0.9708.

## NDVI and Environmental Data

Regression analysis indicated that phenological, topographic, vegetative, and geographic variables were highly significant ( $P < 0.001$ ) sources of variation in NDVI at all levels of the hierarchical framework (table 3). Among provinces, variation in NDVI explained ranged from  $R^2 = 0.206$  for P222 to  $R^2 = 0.553$  for M221. Among the independent variables, time of measurement during the growing season (i.e. June 22 or September 22) explained the largest proportion of variation, followed by elevation and stand basal area. Effects of season, elevation, and stand basal area were generally consistent in magnitude and sign of the variable coefficients: NDVI increased with increasing elevation and stand basal area primarily as a result of greater quantities of green vegetation.

Season of determination was not significant for division 230 because of an interaction between the two provinces. As indicated by the signs of the coefficients for season, NDVI decreased from summer to fall for P231, but increased for P234. Effect of season was consistent among the other ecoregions.

## Discussion

### NDVI and Ecoregions

This study demonstrated that ecoregions explained significant variation in NDVI at several levels of a hierarchical classification framework in the humid eastern US, where landcover consists of forests dominated by relatively uniform arborescent vegetation. Our results parallel those reported by Ramsey and others (1995), who found that nonhierarchical ecoregions of the arid environments of

**Table 3:** Regression coefficients of season, topographic, vegetation, and geographic variables and fit statistics ( $R^2$ , coefficient of correlation;  $S_{y,x}$  standard error of mean) in models of NDVI by hierarchical ecoregion.<sup>1</sup>

Ecoregion	Season	Elevation	B.A.	Latitude	Longitude	$R^2$	$S_{y,x}$
Domain 200	-2.901*	0.010*	0.091*	-0.231*	0.306*	0.313	4.212
Divisions in domain 200							
220	-2.972*	0.009*	0.095*	-0.220*	-0.276*	0.319	4.134
230	-0.714	0.031*	0.016*	-1.917*	-0.537	0.320	5.562
Provinces in division 220							
M221	-3.745*	0.010*	0.046*	1.723*	-2.186*	0.482	2.889
P221	-4.241*	0.013*	0.039*	2.681*	-1.678*	0.474	2.924
P222	-2.215*	0.025*	0.115*	-0.618*	-0.066	0.265	4.388
Provinces in division 230							
P231	-2.928*	0.029*	-0.032	-5.515*	-0.750*	0.430	4.166
P234	10.438*	0.181*	0.123*	-15.680*	23.661*	0.468	7.156

<sup>1</sup>Level of significance: \*=P<0.01.

<sup>2</sup>B.A.: Basal area of stand.

Utah were significantly related to NDVI. Mean NDVI was higher and more variable in our study than in the Utah study. NDVI in the oak-hickory type averaged about 156(±9s.d.) for summer and 153(±8s.d.) for fall whereas NDVI in the Utah study was about 118(±5s.d.) (Ramsey and others 1995). Minimum NDVI was similar for both areas, about 100, indicating a lack of photosynthesizing vegetation. Maximum NDVI, however, ranged from 169 to 178 across the deciduous forested ecoregions and from 115 to 148 in the ecoregions in Utah. Because NDVI is a surrogate variable for on-site quantification of vegetation (Loveland and others 1995), our results suggest that there are ecological differences among most ecoregions in our study area.

One might draw useful conclusions from a single year's results if by-province NDVI rankings did not change from year to year. Ramsey and others (1995) found little annual variation in NDVI, but we found substantial switching in year-to-year rankings of ecoregional NDVI means. This variation served as the experimental error in our tests of significance. We hypothesize that year-to-year differences in NDVI at the season date of measurement could result from a combination of varying annual temperature and precipitation regimes. Spring temperatures that are cooler or warmer than normal would affect development of foliage by the June 22 measurement date, resulting in less or more green photosynthesizing vegetation than average for imaging based on NDVI. In a similar manner, annual variation in the soil moisture regime affects the quantity of vegetation present.

Atmospheric effects are a possible cause of annual variation in NDVI values within and among ecoregions. The NDVI imagery used in our study was uncorrected for atmospheric effects of water vapor, ozone, and Rayleigh scattering. NDVI band 2 (0.75-1.1µm) is particularly sensitive to increased levels of atmospheric water vapor, which tends to reduce estimated NDVI values. The use of biased values of NDVI can reduce the accuracy of estimates of vegetation

moisture content and other predictions. NDVI was not used for predictive purposes in our study. Also, the use of biweekly NDVI composites tends to reduce atmospheric effects because the greenest pixel is used in such composites, which suggests that the image was made when there was the least amount of water vapor in the atmosphere. Clearly, however, use of atmospherically corrected NDVI values is desirable.

Our use of PDSI to quantify meteorological drought accounted for small but significant variation in annual NDVI. Walsh (1987) also found that NDVI was correlated with PDSI. A measure of air temperature for each season by year would likely account for additional variation in NDVI. Annual variation in soil moisture availability may account for some of the variation in NDVI in our study. The PDSI indicated a surplus of soil moisture ( $PDSI > 0.5$ ) for broad, state climatic divisions in 6 years and a deficit ( $PDSI < -0.5$ ) in 3 years. Availability of refined values of PDSI from the weather station nearest each FIA plot would likely have shown stronger relationships in the analysis of covariance.

Because FIA plots are established in forested locations, we were able to use the locations of FIA plots to subsample NDVI values within ecoregions. However, the positional accuracy of these plots to only 0.01 seconds is an important limitation in their usefulness. This lack of accuracy caused us to expand our sample area to the eight neighboring cells surrounding the cell in which the FIA plot supposedly fell. Despite the relative lack of accuracy of inventory plot location and the greater likelihood of including nonforested areas for NDVI determination in the expanded sample area, we consider this method as superior to the total polygon method. That method uses all cells in a polygon for analysis, which could include many that are nonforested, such as urban areas and agricultural fields, thereby potentially increasing variation. Marked improvement in results should be possible with increased location accuracy of plots. One possible drawback to this rationale, however, is exclusion of NDVI values associated with land uses other than forests, a classification factor included in some ecoregion map delineations (Omernik 1995).

## **NDVI and Environmental Variables**

Our study demonstrates a significant association between NDVI and characteristics of field inventory plots. Stand basal area consistently and significantly accounted for small amounts of variation in NDVI. We assume that the relationship would have been stronger if sampling had been restricted to a single 1.1 km cell, instead of the 3.3 km<sup>2</sup> grid that was used. Our findings agree with those of Kremer and Running (1993) who found that characteristics of vegetation on ground-sampled plots were correlated with 1.1 km NDVI imagery.

The explanation of the significance of the other topographic and geologic variables is logical. Elevation was directly associated with NDVI in all of the ecoregions we studied, and is associated with length of growing season, initiation

of spring growth, and onset of winter dormancy, as have been reported in other studies (Ramsey and others 1995, Burgan and Hartford 1993, Loveland and others 1995). Latitude is likely related to variation in temperature within ecoregions and to variation in NDVI. The effect of longitude on NDVI variations is probably related to precipitation, which tends to increase from west to east. In our study area, longitude is probably more closely associated with precipitation than with temperature.

## Conclusions

Remote sensing data can be used to test the relatively uniform, humid environments of the eastern U.S. for uniqueness in some vegetational characteristics. Our test was designed to determine if ecoregions differed based on measurements of NDVI, which quantifies the amount of photosynthesizing vegetation present. Other characterization criteria of ecoregions, including plant species composition and water quality, have proven useful for ground-based validation testing, but NDVI is one of the few variables that can be applied using remote sensing. We found that one difficulty associated with the use of NDVI in the forested eastern U.S. is annual variation in its magnitude. This variation could result from subtle year-to-year climatic effects on vegetation attributable to annual variation in temperature and moisture regimes, or to varying atmospheric conditions associated with a humid climate. Multiple years of NDVI data are needed both to avoid possible bias arising from analysis of atypical data and as a source of experimental error. Results of our study in deciduous hardwoods confirm and extend those of other studies in which NDVI was used to test ecoregion maps in arid environments.

The use of FIA plot locations provides data of sufficient sensitivity for testing and reducing variation between ecological map units. Other studies have used polygons in which all cells are utilized for computation of a single average value of NDVI for a particular time period. This total polygon method adds variation in NDVI that comes from nonforest conditions. However, the large number of sample sites based on inventory plot locations provided data for testing of the within-polygon relationship NDVI has with environmental factors. FIA plots also provided a large amount of useful ancillary information.

NDVI should not be the sole criterion for testing ecoregion hypotheses. However, NDVI evaluation could be used to identify parts of ecoregions warranting further investigation or review. NDVI should be considered a tool for preliminary screening. NDVI and inventory plot analysis is a relatively inexpensive and readily available tool that could be used by persons who do not have knowledge of GIS techniques and expensive GIS software. Although we used relatively simple methods, additional more sophisticated techniques are available, such as correcting for variation in atmospheric conditions.

In conclusion, our study provides methodology for using inventory data and remote sensing imagery for testing hypotheses about ecoregion map units. The use of FIA inventory plots to provide specific locations for sampling and information on the vegetation present, in conjunction with NDVI data obtained by remote sensing, provides a method suited to testing of ecoregion maps. The purpose of this investigation was not to develop or refine mapped ecological units, but to examine the potentials of NDVI data as a tool for use in the future development and testing of map units. Our results suggest that NDVI may be well suited for this purpose.

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