

MODIS enhanced vegetation index predicts tree species richness across forested ecoregions in the contiguous U.S.A.

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Abstract

With the expectation of major shifts in climate, ecologists have focused attention on developing predictive relationships between current climatic conditions and species diversity. Climatic relationships appear best defined at regional rather than local levels. In reference to tree diversity, process-based models that express gross primary production (GPP) as an integrated function of climate seem most appropriate. Since 2000, NASA's MODIS satellite has provided composite data at 16-day intervals to produce estimates of GPP that compare well with direct measurements. The MODIS enhanced vegetation index (EVI), which is independent of climatic drivers, also appears a good surrogate to estimate seasonal patterns in GPP. In this paper we identified 65 out of 84 delineated ecoregions distributed across the contiguous U.S.A., within which sufficient (≥ 200) Federal Inventory and Analysis survey plots were available to predict the total number of tree species, which varied from 17 to 164. Four different formulations of EVI were compared: The annual maximum, the annual integrated, the growing season defined mid-point and growing season averaged values. The growing season mid-point EVI defined the beginning and end of the active growing season. In all formulations of EVI, a polynomial function accounted for about 60% of the observed variation in tree diversity, with additional precision increasing to 80% when highly fragmented ecoregions with $< 50\%$ forest cover were excluded. Maps comparing predicted with measured tree richness values show similar patterns except in the Pacific Northwest region where a major extinction of tree genera is known to have occurred during the late Pliocene. The extent that these relationships remain stable under a changing climate can be evaluated by determining if the MODIS climate-driven estimate of GPP continues to match well with EVI patterns and systematic resurveys of forest vegetation indicate that tree species are able to adjust rapidly to climatic variation.

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1. Introduction

Over the last few decades, there has been an expanded effort to predict biological diversity as a function of climate at both the regional (Currie & Paquin, 1987; Hawkins et al., 2003; O'Brian, 1998; Venevsky & Veneskaia, 2003) and global scale (Gaston, 2000; Kleidon & Mooney, 2000; Latham & Ricklefs, 1993). This expanded interest is justified on the basis of accelerated

extinction and the expectation that a major reconfiguration of vegetation patterns is predicted during this century (Iverson & Prasad, 2001). The paleobotanical record provides evidence that a changing climate obliterates major associations and causes new ones to be formed (Axelrod et al., 1991). For this reason most analyses have been based on species range maps rather than plant associations.

Although there is considerable debate about the proper scale of analysis and the extent that causal relationships associated with competition and disturbance apply over a range of spatial scales (Huston, 1999; O'Brian, 1998; Whittaker & Field, 2000), there is a consensus that historical factors must be recognized to explain differences in the pool of species present in different

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locations that have similar climates (Qian & Ricklefs, 2000), and in the distribution of endemics (Whittaker & Field, 2000). Conventionally, climatic relationships with species diversity are first tested, and if inadequate, historical factors are then investigated. At regional scales, the degree of disturbance and fragmentation of the landscape may still apply, but these factors are generally muted in comparison to climatic effects (see review by Sarr et al., 2005).

Temperature and moisture are the two variables encompassed in most climatic analyses, usually in the form of annual precipitation and evaporation (potential or actual).

Ecologically, one would prefer to analyze climatic effects seasonally and in reference to how organisms directly respond (Mason & Langenheim, 1957). The integrated response of vegetation to climate is expressed as growth, or net primary production, NPP. A direct correlation between productivity and species richness is, not surprisingly, generally better than those derived with annual indices of climate (Hawkins et al., 2003).

The modeling of productivity as a function of climate is embedded in process-based models that predict CO₂ and water vapor exchange as well as the cycling of carbon and nutrients within and through ecosystems (see review by Landsberg, 2003). Through sensitivity analyses, the relative importance of various climatic factors on production can be assessed and mapped spatially (e.g., Nemani et al., 2003). Such process-based models include seasonal water balances and recognize the importance of radiation interception and utilization by vegetation. Process-based growth models are particularly well developed and tested for forests, which leads us to the premise: *That tree diversity should be predictable if dependent on current climatic patterns. The extent that such relationships remain viable under a rapidly changing climate, however, will require periodic retesting.*

We are fortunate in the United States to have access to survey records acquired by the Federal Inventory and Analysis (FIA) program (<http://www.fia.fs.fed.us/>) that systematically record the composition of forest vegetation across the country. These surveys are much more accurate than species range maps and offer a sound basis for developing and testing correlations between tree richness and productivity at different spatial scales, now and in the future.

Although the productive capacity of the land can be fairly accurately predicted with process-based models if sufficient information on soils and climate is available (Coops & Waring, 2001; Coops et al., 2001; Ollinger et al., 1998), such information is often lacking or is imprecise (Swenson et al., 2005). Alternatively, we might consider modeling GPP, as it is approximately twice the value of NPP (Gifford, 2003; Waring et al., 1998). In the states of Oregon and Washington, GPP, estimated from extrapolation of climate and soil data, accounted by itself for 80% of the observed variation in tree richness at a spatial resolution of 10 km (Swenson & Waring, in press).

Satellite-derived estimates of gross primary production (GPP) are readily available as products generated using NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). Alternatively, we chose to use the MODIS enhanced vegetation index as a surrogate for GPP that is independent of

climatic data and therefore accurate, without extrapolation to a spatial resolution of 1 km. Both estimates of GPP are in general agreement where they have been compared with values generated at sites where CO₂ and water vapor exchange were continuously monitored (Rahman et al., 2005).

In this paper we test the extent that EVI correlates with tree richness data from 65 recognized ecoregions across the contiguous U.S.A. where FIA survey data were adequate to predict the pool size of tree species present.

2. Methods

2.1. Ecoregions

To obtain a general description of the ecological zones across the contiguous USA we chose the level III classification of ecological regions of North America available from the US Environmental Protection Agency (<http://www.epa.gov/wed/pages/ecoregions.htm>). Earlier attempts at classifying ecoregions proved too broad in that many species were included in ecoregions with ranges that did not overlap. The level III classification defines 84 ecoregions within the boundaries of the 48 contiguous states at an approximate scale of 1:30 million. We tested the assumption (CEC, 1997) that each ecoregion could be considered unique, based on similarities in climate, geology, landforms, and flora by confirming that as few as 200 survey plots would provide a good estimate of the total pool of tree species present within an ecoregion.

The amount of forested area varies considerably by ecoregion. To ensure that only forested pixels were used in the analysis, we utilized a second land cover data set derived and distributed as part of the MODIS standard data products. This land cover classification (MOD12Q1, Collection 3, developed by the University of Maryland, UMD (Carroll et al., 2003; Hansen et al., 2000), is also utilized in the analysis of the MODIS GPP product (Zhao et al., 2005). The UMD classification is pixel-based at 1000 m spatial resolution and defines 15 classes covering the major biomes across the globe. To restrict our analysis to forested environments, we combined five forest classes (evergreen needleleaf, evergreen broadleaf, deciduous needleleaf, deciduous broadleaf, and mixed forests) into one mask which was then applied in all subsequent processing. The UMD classification is relatively stable, a desirable feature for our analysis because tree survey data are acquired over a decade.

2.2. Tree richness data

Tree richness values for ecoregions were computed from a total of 174,207 FIA field surveys (44,408 fixed and 129,799 variable area plots). The number of FIA plots present averaged 1540 per ecoregion with a range from 0 to 18,982 across the 84 ecoregions.

To attain a good estimate of tree richness for the largest number of ecoregions, we restricted our analysis to 65 ecoregions with 200 or more FIA field survey plots. With a sample size of 200, an asymptote in species number was

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