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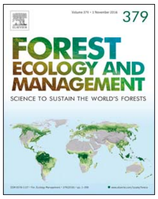

Modeling forest site productivity using mapped geospatial attributes within a South Carolina Landscape, USA

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ABSTRACT

Spatially explicit mapping of forest productivity is important to assess many forest management alternatives. We assessed the relationship between mapped variables and site index of forests ranging from southern pine plantations to natural hardwoods on a 74,000-ha landscape in South Carolina, USA. Mapped features used in the analysis were soil association, land use condition in 1951, depth to groundwater, slope and aspect. Basal area, species composition, age and height were the tree variables measured. Linear modelling identified that plot basal area, depth to groundwater, soils association and the interactions between depth to groundwater and forest group, and between land use in 1951 and forest group were related to site index (SI) ($R^2 = 0.37$), but this model had regression attenuation. We then used structural equation modeling to incorporate error-in-measurement corrections for basal area and groundwater to remove bias in the model. We validated this model using 89 independent observations and found the 95% confidence intervals for the slope and intercept of an observed vs. predicted site index error-corrected regression included zero and one, respectively, indicating a good fit. With error in measurement incorporated, only basal area, soil association, and the interaction between forest groups and land use were important predictors ($R^2 = 0.57$). Thus, we were able to develop an unbiased model of SI that could be applied to create a spatially explicit map based primarily on soils as modified by past (land use and forest type) and recent forest management (basal area).

1. Introduction

Many forest management decisions require a spatially explicit estimate of forest site productivity, or mean annual increment of growth over a defined interval, to assess species-site suitability, silvicultural alternatives, carbon sequestration capacity, wildlife habitat suitability and climate impacts. Spatially explicit estimates of forest productivity across entire landscapes are a challenge as direct measurement of growth potential and associated soil chemical or physical properties are traditionally expensive and, therefore, limited to smaller inventory samples (Swenson et al., 2005). Although remote sensing technology like LiDAR (Light Detection and Ranging) can measure tree heights with great precision and resolution over large landscapes, it is not widely adopted for estimating potential productivity at this time due to the need to extensive field plot calibration (Gatziolis, 2007). Geospatially-mapped attributes of climate, soil, topography, prior land use and silviculture treatment offer an opportunity to cost-effectively create spatially explicit landscape estimates of productive potential for management. However, they may not reliably represent causal variables, as their accuracy and precision is often unknown and they scale differently in relation to their effects on productivity (Aertsen et al., 2012).

Several studies have estimated productivity over very large climate gradients. Site index (SI) is the most commonly used, relatively density-independent quantitative indicator of site productivity (Avery and Burkhart, 2002). Site index for Norway spruce (*Picea abies* (L.) Karst) was modelled successfully over Bavaria, Germany using a combination of temperature, water supply and soil base saturation parameters derived from mapped features (Brandl et al., 2014). Site index for cork oak (*Quercus suber* L.) was predicted across Portugal using a combination of derived water availability and soil properties obtained from large thematic maps of climate and geology (Paulo et al., 2015). Soil water availability was derived from mapped climate conditions and soil

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units to estimate SI across the southern USA for managed and unmanaged loblolly pine (*Pinus taeda* L.) (Sabatia and Burkhart, 2014). A regional model of SI for conifers and hardwoods across the eastern USA was created by modeling SI values obtained from U.S. Forest Service, Forest Inventory and Analysis data with climate and soil variables (Jiang et al., 2015).

In contrast, successful attempts to use mapped geospatial attributes under identical climate conditions to predict productivity are limited (Payn et al., 1999). In the southeastern USA, mapped taxonomic soil series are weakly related to species productivity (Van Lear and Hosner, 1967). However, predictive relationships can be found if specific soil conditions are measured. In the coastal plain, depth of organic layers or depth of the argillic horizon are related to productivity (Coile and Schumacher, 1953; Shoulders and Tiarks, 1980). In high water table regions, drainage conditions and phosphorus availability are important predictors (Comerford and Pritchett, 1982; Morris and Campbell, 1991). A combination of chemical and physical soil properties within the upper 15 cm of the mineral soil was strongly correlated to site index across 15 loblolly pine plantations in the southern USA (Subedi and Fox, 2016). Unfortunately, these chemical or physical soil attributes are rarely mapped over the landscape or sampled sufficiently to represent the variability in these attributes. Landscape attributes that control productivity are also confounded by prior agricultural land use and forest management treatments (Clutter and Dell, 1978; Martin and Jokela, 2004).

The goal of this research was to create a reliable model that enabled the construction of a spatially-explicit map of SI. A spatially continuous Modeling process, such as continuous cartographic Modeling or generalized kriging, requires representative observations for the entire landscape (Kemp, 2008). Therefore, our objective was to determine if SI measurements from inventory plots were related to mapped soil, groundwater, stocking, prior land use and forest group attributes across a continuous landscape in South Carolina, USA within identical climate conditions.

2. Methods

2.1. Site description

The study location was the U. S. Department of Energy, Savannah River Site (SRS), an 80,000-ha National Environmental Research Park in South Carolina (Kilgo and Blake, 2005). It is located on the Upper Coastal Plain and Sandhills physiographic provinces in South Carolina, USA (Fig. 1). The site was established in 1950 and managed for various natural resources compatible with the Department of Energy defense missions associated with the processing, storage and disposition of nuclear materials (USDA Forest Service - Savannah River, 2005). Agrarian practices have impacted more than 70% of the landscape since European settlement in the late eighteenth century (White and Gaines, 2000). When the SRS was established, approximately 33,000 ha were in farm fields with the balance in cutover forest with low stocking and some intact forests (Kilgo and Blake, 2005). Only about 2000 ha were in pine plantations in 1950; these plantations were established on farm fields between 1938 and 1948.

Currently, three major forest types are present: pine plantation, mixed pine-hardwood forest, and hardwood forest. Of the 80,000 ha at SRS, about 74,000 ha are classified into one of these three categories and are mapped as about 6000 discrete stands. Between 1951 and 1970 the agricultural fields and cutover forests were converted to plantations of loblolly pine, longleaf pine (*P. palus*tris Mill.) and slash pine (*P. elliottii* Engelm. var. *elliottii*) with limited or no attention to soil conditions. This practice resulted in plantations of the three pine species ($>$ 80% pine) in adjacent stands throughout the landscape. Site preparation on these areas consisted of mechanical furrows or disking to provide weed control and bare soil for planting. Treatment of hardwood tree competitors with herbicides occurred on cutover forest sites, but these treatments did not impact shrub or grass competition with planted trees. Disking and raking of residual debris occurred in the 1980's and early 1990's followed by an application of herbicide and then prescribed fire prior to machine planting. There was no operational planting of genetically improved high yield pines or routine fertilization. Mixed pine-hardwood forest exist predominately in upland woodlots adjacent to old farm fields in a continuous gradient down through riparian zones, but are present in on old farm field due to natural regeneration. These stands are distinct from the plantations because they represent natural regeneration of loblolly pine intermixed with various hardwood species such as oaks (*Quercus* spp.), hickories (*Carya* spp.), sweetgum (*Liquidambar styraciflua* L.) and occasional longleaf pines. Finally, hardwood-dominated forests have fewer pines ($<$ 20% pine by stocking). They are similar to mixed pine-hardwood forests in composition and are harvested periodically and regenerated naturally.

The current land management objectives include support for the Department of Energy defense and research missions, a continuous stream of revenue, recovery of endangered and threatened species and restoration of important habitat conditions for plants and animals (USDA Forest Service - Savannah River, 2005). Today, rotation ages range from 50 to 120 years depending upon management area and species. Intermediate thinning and clear felling occurs on about 2000 ha and 300 ha, respectively, each year (Kilgo and Blake, 2005). Where clear felling is conducted, site preparation currently consists of a single application of herbicide followed by burning. Longleaf pine, loblolly pine or various hardwood species are then planted. When intermediate thinning is performed, smaller diameter and poorer quality trees are preferentially removed, subject to maintaining spacing between trees. First thinning begins between ages 15 and 30 years with subsequent thinning done periodically at 10- and 20-year intervals, depending upon stocking levels.

2.2. Site productivity

Site index, the mean height of dominant and co-dominant trees at a standard age of 50 years, was used as an indicator of site productivity. In 2000, we conducted a forest inventory of the entire SRS from which we obtained SI data (Parresol et al., 2012). Plots were established on a 1000-m × 1000-m grid across the entire SRS, resulting in more than 600 geo-referenced plots across the landscape (Fig. 1). A plot consisted of a cluster of five subplots spaced 21.3 m apart along a line within a stand of the same forest type and age. A variable-radius prism measurement with an 8.61 basal area (BA) factor ($m^2\,ha^{-1}$) was used for sampling overstory trees. All prism samples from the five subplots were combined. Subplot measurements included BA, total tree height, diameter at breast height (DBH), and species for all prism trees. Tree age at DBH (1.3 m above ground) was determined from tree cores for two to eight selected, apparently undamaged, dominant or codominant trees within the five subplots.

Pine trees, when available as dominants or co-dominants, were selected for determining SI. This led to 2361 SI trees representing 53% loblolly, 25% longleaf, 15% slash pine and 7% various hardwood species. We excluded SI sample trees under 18 and over 95 years old due to unreliable SI estimates at these ages. This restricted the population to plantations and naturally regenerated stands established prior to 1980. For the mixed pine-hardwood forest group (50 plots) we excluded hardwood trees and retained only pine SI values which led to a distribution of pine SI trees that were approximately 80% loblolly pine, 15% longleaf pine and 5% slash pine trees. We calculated SI from core age and total height using Carmean's SI prediction equations at base age 50 for the individual tree species (Carmean et al., 1989). The equations used within his publication are: loblolly pine, Fig. 111; longleaf pine, Fig. 93; slash pine, Fig. 85; white oak (Q. alba) Fig. 37; southern red oak (*Q. falcata* Michx.), Fig. 37; laurel oak (*Q. laurifolia* Michx.), Fig. 44; black oak (*Q. velutina* Lam.), Fig. 49; post oak (*Q. stellata* Wangenh.),