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Research Article

Effects of Landform on Site Index for Two Mesophytic Tree Species in the Appalachian Mountains of North Carolina, USA

W. Henry McNab

Southern Research Station, USDA Forest Service, 1577 Brevard Road, Asheville, NC 28806, USA

Correspondence should be addressed to W. Henry McNab, hmcnab@fs.fed.us

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The effects of soil and topographic variables on forest site index were determined for two mesophytic tree species, northern red oak (*Quercus rubra* L.) and yellow-poplar (*Liriodendron tulipifera* L.) in the Southern Appalachian Mountains of North Carolina. Stand variables included soil solum thickness, soil A-horizon thickness, elevation, aspect, slope gradient, and landform index. Landform index is a recently devised environmental variable that has been used to quantify the influence of topography surrounding a stand on productivity. Regression analysis indicated that among the variables only landform index had a significant ($P < .05$) relationship with site index and explained 46 percent of the variation for northern red oak and 56 percent for yellow-poplar. Plot data from this study were also used to validate a previously developed prediction equation for estimating yellow-poplar site index and results indicated that unbiased estimates would be within 2.5 m. Results from this study suggest that landform accounts for variation in site index of mesophytic species in mountainous terrain that is not explained by conventional stand variables associated with soil and topography.

1. Introduction

Forest site quality prediction models have often used environmental variables associated with availability of soil moisture during the growing season, such as aspect, slope gradient, slope position (e.g., upper, lower), and soil texture [1]. Landforms (e.g., cove, ridge) also affect soil moisture [2] and slope position is often used as a surrogate in soil-site models [3]. However, the two-dimensional categories of slope position are a poor substitute for landform because they may not account for environmental factors, such as the effects of wind that are associated with the 3-dimensional shape of land surfaces [4, 5]. Classes of landform have accounted for significant variation in site index for some species [6, 7], but determination of categorical variables in the field is subjective and their use in regression analysis can be problematic [8]. Perhaps the primary reason landform has not been included in studies of forest site quality is lack of a suitable and easily applied method for its quantification, which is available for other topographic-related environmental variables such as elevation and aspect.

An objective measure of landform as a continuous variable has been devised that overcomes many of the problems associated with conventional categories such as slope or ridge [9]. The landform index (LFI) quantifies the environmental influence of topography on a stand and has accounted for significant variation in site quality of a mesophytic tree species (e.g., yellow-poplar) in the Southern Appalachian Mountains [9] and was important in a multivariate analysis of the landscape distribution of species assemblages [10, 11].

LFI has been a useful independent variable in a number of recent multivariate ecological classification studies [12, 13], but little is known about its value in other applications, such as forest soil-site studies. A range of environmental effects are logically associated with landform, particularly soil moisture and soil physical properties. Although LFI in combination with other topographic variables is important for predicting site index of yellow-poplar, it has neither been evaluated in combination with soil variables nor has it been evaluated for prediction of site index for other tree species. In addition, the value of LFI for field application to evaluate site quality could be strengthened by using an independent data set to test an early model for prediction of yellow-poplar site index [9].

Here, I report results of a study to evaluate the relative value of LFI for prediction of forest site quality. My study had two objectives: (1) determine the effect of landform, in combination with conventional topographic and soil variables, on site index of hardwood tree species and (2) with an independent data set, test the accuracy of a previously developed model based on LFI for predicting site index of yellow-poplar [9]. The results of this study are intended to provide additional insight into environmental factors affecting forest site quality in mesic stands of mountainous landscapes in the Southern Appalachians.

2. Methods

2.1. Study Area. I conducted the study in the Southern Appalachian Mountains of North Carolina (Figure 1). The climatic regime of this area is classified as temperate humid. Elevation ranges from 600 m to more than 2000 m. Mean monthly air temperature ranges from 2.5°C in January to 23.5°C in July. Annual precipitation varies with elevation and ranges from about 950 mm to over 1,500 mm; it is distributed uniformly with no pronounced wet or dry seasons [14]. Geologic formations are primarily Precambrian metaigneous and metasedimentary gneisses and schists with differing amounts of quartz, feldspars, and micas that have weathered to form highly dissected landscapes of low to moderate relief [15]. Soils are generally deep (>100 cm), acidic (pH < 5.5), and infertile except in valleys where fertility is higher likely resulting from greater depth of soil and organic matter associated with colluviums [15]. In general, soils present in the study areas are uniform with productivity differing mainly in water-holding capacity that is probably associated with solum depth and texture.

Forests in the study area are characterized by a canopy of deciduous hardwoods [15]. Ridges and upper to middle portions of slopes are typically dominated by chestnut oak (*Q. prinus* L.), and scarlet oak (*Q. coccinea Muenchh.*). Many lower slopes and coves are dominated by yellow-poplar (*Liriodendron tulipifera* L.) and lesser amounts of northern red oak (*Q. rub*ra L.) (hereafter referred to as red oak). White oak (*Q. alba* L.) occurs throughout, along with midstory species such as red maple (*Acer rubrum* L.), sourwood (*Oxydendrum arboreum* (L.) DC), and flowering dogwood (*Cornus florida* L.). Common conifers include shortleaf pine (*Pinus echinata* Mill.) and pitch pine (*P. rigida* Mill.) on ridges and eastern hemlock (*Tsuga canadensis* (L.) Carr.) along streams. Eastern white pine (*Pinus strobus* L.) is a minor component of many upland hardwood stands. American chestnut (*Castanea dentata* (Marsh.) Borkh.) was a major canopy constituent of many stands before being eliminated by an introduced pathogen (*Cryphonectria parisitica*) in the 1920s. About two-thirds of the study area is forested.

2.2. Site Quality. I obtained data from 41 forest stands sampled by the Natural Resources Conservation Service (NRCS), an agency of the U.S. Department of Agriculture. The stands were selected by NRCS primarily to describe natural variation in characteristics of soil series taxonomic units [16] and also to determine productivity of tree species associated with the soil mapping units. Primary criteria for stand locations were diversity of soil taxonomic units, lack of recent observable disturbance, and an even-aged canopy ranging between 30 and 70 years of age. Each stand was located within a contiguous mapped soil unit where soil characteristics were well within the acceptable range for that series, as determined by examination of the profile in an excavated pit.

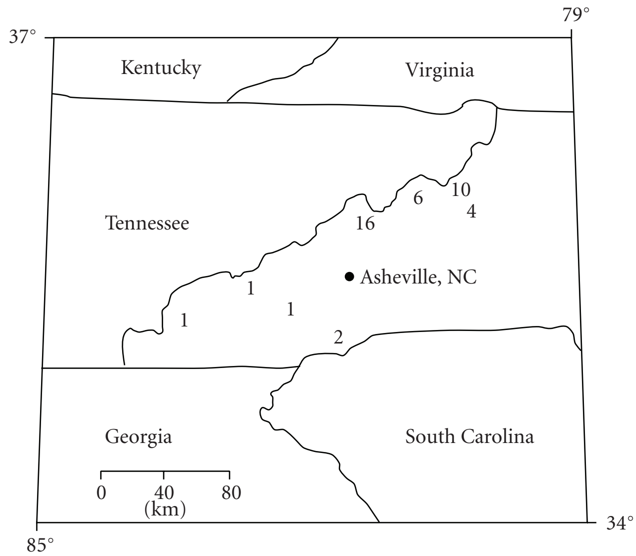

Figure 1: Number of plots and approximate location of stands sampled in the Southern Appalachian Mountains of North Carolina, USA.

Forest site quality was quantified using site index, the average total height of the dominant and codominant stand component at 50 years [17]. Equations to determine site index for any combination of current tree age and height are available for many commercial forest tree species [18]. In order to determine stand age from annual ring counts, increment cores were extracted from three or more suitable trees at a stem height of 1.37 m. Total height was measured to the nearest 0.3 m with a handheld clinometer on three or more dominant or codominant trees for one or more species. Nine tree species occurred on 1 to 17 stands; site index was determined for each species in each stand. Field data were collected from sample trees that met the criteria for site index determination [17]. The data were well suited for this study of site quality because sample stands had been selected primarily for another purpose (soil pedon description), thereby reducing bias and subjectivity in my application of modeling site index in relation to soil and topographic environmental variables.

2.3. Soil and Topographic Variables. Six soil and topographic variables were measured at each stand sampled.

(i) Thickness (cm) of the soil A-horizon from an excavated pit.

(ii) Thickness (cm) of the soil solum from an excavated pit.

(iii) Elevation (m) from a topographic map.

(iv) Aspect (degrees azimuth) with a hand-held compass.

(v) Gradient (percent), or slope steepness, with a hand-held clinometer.

(vi) Landform index (percent expressed as a decimal) with a hand-held clinometer.

An explanation of the development of LFI is presented in detail elsewhere [9]. Briefly, however, LFI is defined as the mean inclination of the horizon (i.e., the apparent intersection of the earth and sky) in relation to a location in the stand being studied. An example illustrates the necessary decisions, methods, and calculations necessary to determine LFI for a location. First, the observer must determine the number of samples of the population of inclinations to the horizon around a stand that are needed to estimate the mean with some desired precision. I have found that eight samples are usually adequate in the subdued mountainous topography of the Southern Appalachians, but the number may range from 1 to more than 360 depending on variability of the landscape surrounding the stand. Generally, the same number of inclination samples should be used for all stands included in the study.

Assume, for example, that the observer decides to sample the inclination to the horizon in five directions of equal azimuth (i.e., the horizontal angular distance from a reference direction) at a location in a stand. A handheld clinometer, graduated in either percent or degrees, is adequate for this purpose. Data for quantifying LFI are obtained using a stratified random sampling method at the selected location in the stand. Beginning in a random azimuth, for example 254°, and continuing in increments of 72° (i.e., 360°/5 directions) the inclination to the horizon at azimuths of 254°, 326°, 38°, 110°, and 182° are measured as +43%, +24%, 0%, −3%, and +38%, respectively. The LFI for the sample stand is calculated by the relationship

$$\overline{\text{LFI}} = \frac{\sum I_i}{n}, \tag{1}$$

where $\sum I_i$ is the algebraic sum of inclinations to the horizon sampled in equal increments of azimuth from a location in the stand n is the number of inclinations sampled.
Solving (1) using the example data, with inclination percents expressed as decimals, results in LFI calculated as

$$\text{LFI} = \left(\frac{(0.43 + 0.24 + 0.0 - 0.03 + 0.38)}{5}\right) = \frac{1.02}{5} = 0.204. \tag{2}$$

Similar values of the mean inclination to the horizon can result from many variations of landforms. Horizon inclinations from different stands that result in similar values of LFI, however, are presumed to account for similar proportions of variation of stand response variables. As with other important variables used to characterize the physical environment of a stand at a location on a landscape, LFI has little utility for use in a prediction equation until its relationship is determined for a response variable, which is one of the objectives of this study.

2.4. Data Analysis. Species present in ≥10 of the 41 stands sampled were retained for analysis. Of the six environmental variables included in this study, only aspect required transformation. Because azimuth is a circular measurement of aspect, I transformed it using the cosine relationship described by Beers et al. [19]. LFI is a continuous measure and was used in the analysis as a common topographic variable. I used t-tests to (1) determine significant correlation between pairs of soil and topographic variables for each species and (2) detect differences between environmental variables associated with each species. I used multiple regression analysis to determine the relationship between the dependent variable of site index and the six independent variables for each species. I evaluated coefficients of the independent variables for significance using F-tests under the null hypothesis that the parameters were equal to 0 and thus had no real effect on site index.

Two types of models were developed for each species: overfitted and parsimonious. Overfitted models may include variables that account for little variation in site index and are used primarily for exploratory purposes to determine the relative importance among the variables of interest [8]. A parsimonious model was developed for each species that included only the single most significant environmental variable identified in the overfitted models. Inclusion of additional variables in the parsimonious model was not warranted because of the small size of the data set. Equation coefficients are omitted because model development was not the objective of my study and the available data set was inadequate for that purpose. Tests of significance were made at the 0.05 level of probability.

2.5. Model Validation. I used data from the stands where yellow-poplar was present for an independent validation of a previous model [9] developed for prediction of site index using LFI. The previous model was a prototype that had been developed for a larger region of the Southern Appalachian Mountains, which included the smaller area of this study, and is referred to as the SAM model. Validation was done using scatter plotting and the microcomputer program DOSATEST [20]. The DOSATEST program, which tests mean bias and precision of a prediction equation with an independent data set, implements rationale for accuracy developed by Reynolds [21]. Bias, defined as the average error in predictions made by the model, was calculated as the mean difference between actual and predicted site index. Precision was the tolerance interval that delineated 95 percent confidence intervals for 95 percent of future errors.

3. Results

Nine tree species were present in the 41 sample stands. Two species were present in ≥10 stands, red oak ($n = 17$)

Table 1: Mean and range of site index, soil, and topographic variables by species for stands sampled in the Southern Appalachian Mountains of North Carolina, USA.

Model variables	*Red oak* (n = 17) Mean	Range	*Yellow-poplar* (n = 14) Mean	Range
Site index (m)	25.5	18–30	32	25–38
A-horizon thickness (cm)	15.8[a]	8–36	22.1[a]	8–41
Solum thickness (cm)	83.2[a]	36–152	89.6[a]	43–140
Elevation (m)	966.6[a]	442–1329	909.4[a]	646–1165
Aspect (deg)	159.3[a]	45–330	186.3[a]	10–355
Gradient (percent)	28.9[a]	10–60	20.7[a]	2–38
Landform index	0.133[b]	0.01–0.27	0.225[b]	0.08–0.38

[a] Indicates no significant difference ($P < .05$) between the two species.
[b] Indicates significant difference ($P < .05$) between the two species.

and yellow-poplar (n = 14), and were retained for analysis (Table 1). Broad overlap occurred in the ranges of environmental variables measured in stands occupied by the two species. Among the six environmental variables measured in the stands where yellow-poplar occurred, only elevation and LFI were significantly correlated ($r = -0.53$, $P = .05$). For red oak stands, however, thickness of the A-horizon was correlated with elevation ($r = 0.50$, $P = .04$) and particularly with solum thickness ($r = 0.82$, $P = .001$). The low level of correlation between the environmental variables indicated that the effects of multicollinearity would be problematic only if both soil variables were included in the site index model for red oak. Mean LFI was the only variable that differed significantly ($P < .05$) between stands where the two species were present.

3.1. Environmental Relationships with Site Index. Simple correlation coefficients between site index and each of the environmental variables were generally low ($r < 0.2$) and, except for elevation and LFI, were not significant for either species (Table 2). The Pearson correlation coefficients between site index and LFI were $r = 0.75$ ($P = .0005$) and $r = 0.73$ ($P = .003$) for red oak and yellow-poplar, respectively.

The relative importance of variables in the overfitted multiple regression models was generally similar to that for the simple correlations (Table 2). With the six environmental variables present in the model, LFI alone accounted for significant ($P < .02$) variation of site index for both species. Elevation did not account for significant variation of site index when included with LFI for the overfitted prediction model of either species. The relationships for both species were significantly ($P < .05$) associated with predicted site index and accounted for 46 percent of the variation in site index of red oak and 56 percent for yellow-poplar.

Parsimonious site index regression equations were developed for both species that utilized LFI (Figure 2), which was the only environmental variable that accounted for significant variation in the overfitted models. Similarity of regression slopes suggests common response to LFI by both species. Comparison of the two simple linear regression

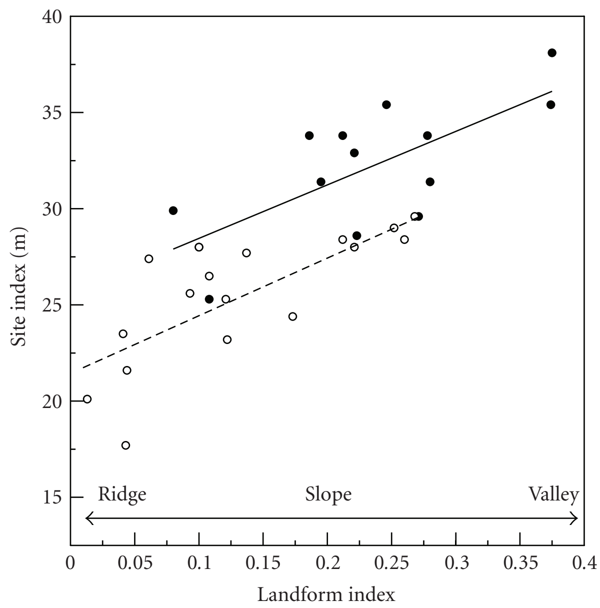

Figure 2: Comparison of linear models for predicting site index from landform index for northern red oak (open circles) and yellow-poplar (closed circles) in the Southern Appalachian Mountains of North Carolina, USA. Classes of landform associated with values of the landform index are shown above the x-axis.

equations indicated no significant ($F = 3.65$, $P > .05$, $df = 1,27$) difference between slopes (beta coefficients), but highly significant ($F = 7.75$, $P < .01$, $df = 1,29$) differences between intercepts (alpha coefficients). Therefore, a single regression line cannot be used to quantify the relationship between site index and LFI for red oak and yellow-poplar.

3.2. SAM Model Validation. LFI for 11 of the yellow-poplar stands in this study was within the range of data used to develop the SAM model (0.15–0.40), but LFI was lower (< 0.15) for three stands (Figure 3). However, site index observed in the 14 stands in this study was all within the 95% confident interval for future values predicted by the SAM model (Figure 3). Fifty seven percent of the observed values of site index were within 2 m of the value predicted by the SAM model. Observed yellow-poplar site index was significantly correlated ($r = 0.73$, $P = <.01$) with values predicted by the SAM model (Figure 3 inset). Even though correlation between observed and predicted site index was high, the SAM model over-predicted site index by 0.546 m. The DOSATEST analysis indicated that, however, this bias is not significantly different from zero and that future errors will be within a prediction interval of 5.26 m.

4. Discussion

Among the six soil and topographic variables examined for their influence on site quality of forest hardwood tree species, only elevation and LFI were correlated with site index. The significantly smaller value of mean LFI for red oak (0.133) compared to that for yellow-poplar (0.225)

Table 2: Pearson correlation coefficients (r) of environmental variables with site index and overfitted regression significance levels ($P > t$) for a site index model with all independent environmental variables by species for stands sampled in the Southern Appalachian Mountains of North Carolina, USA.

Environmental variable	Pearson correlation (r)		Variable significance ($P > \|t\|$)	
	Red oak	Yellow-poplar	Red oak	Yellow-poplar
A-horizon thickness	−0.06[a]	0.23[a]	0.82	0.89
Solum thickness	0.02[a]	−0.08[a]	0.78	0.1
Elevation	−0.50[b]	−0.58[b]	0.16	0.85
Aspect	−0.07[a]	0.03[a]	0.93	0.61
Gradient	0.10[a]	−0.14[a]	0.5	0.1
Landform index	0.75[b]	0.73[b]	0.02	0.01
Model significance	–	–	0.05	0.05

[a]Pearson correlation coefficient was not significant at $P < .05$.
[b]Pearson correlation coefficient was significant at $P < .05$.

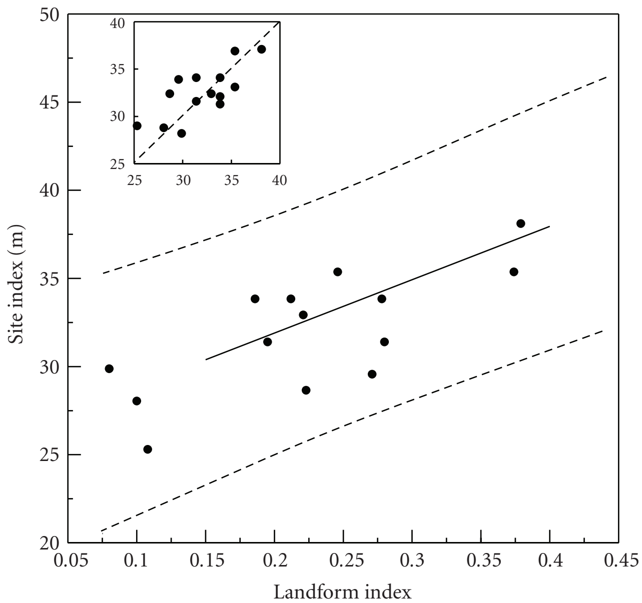

Figure 3: Observed site index for yellow-poplar from the 14 stands sampled in this study was within the 95% confidence limits (two dashed lines) for individual predictions from a model (solid line) reported in a previous study [9] conducted throughout the Southern Appalachian Mountains (SAM). The length of the solid line indicates the range of landform index (0.15 to 0.40) used in development of the SAM model. The inset shows the significant relationship ($r = 0.72, P < .01$) between yellow-poplar site index observed in this study (x-axis) and site index predicted by the SAM model (y-axis). The diagonal dashed line in the inset represents perfect correlation between observed site index and site index predicted by the SAM model.

indicates that red oak stands tended to occur on linear to concave landforms (e.g., slopes to valleys), but yellow-poplar was associated with concave landforms (e.g., valleys). Only LFI accounted for significant variation in site index for both red oak and yellow-poplar in the overfitted regression models that included all of the measured environmental variables. Although elevation was significantly correlated with site index for both species (Table 1), its effect was not important in the regression models likely because it was also slightly correlated with LFI for red oak ($r = -0.33$) and yellow-poplar ($r = -0.39$). Callaway et al. [22] found that productivity of forested sites in the central Great Smoky Mountains was influenced most strongly by an index of landform weighted by aspect; soil variables were also significant, but of minor importance. In the Southern Appalachian Mountains of northeastern Georgia, Ike and Huppuch [6] reported that site index of red oak and yellow-poplar were associated with landform classes (e.g., valley, ridge). My results are in general agreement with theirs [6] and more clearly quantify the effects of landform on site quality for red oak and yellow-poplar.

The lack of significance of the conventional topographic variables with site index was not unexpected. My finding that aspect was not important as a site factor for either species agrees with results from several studies in the Blue Ridge province. Whittaker [23] reported that aspect seemed to have little influence on forest productivity in the Smoky Mountains, perhaps because annual precipitation is ample and well distributed. Helvey et al. [2] found that soil moisture in the Southern Appalachians was not associated with aspect between 600 m and 1500 m elevation. However, Ike and Huppuch [6] reported decreasing site index of red oak from northerly to southerly aspects, but little difference between east and west aspects.

The relative importance of soil characteristics on site quality varies in the Southern Appalachian region. My finding that thickness of the A-horizon and solum thickness did not influence site index agrees with results of Ike and Huppuch [6]. However, in the less mountainous Appalachian Piedmont, the study of site quality by Della-Bianca and Olson [24] suggested an increased importance of soil variables relative to topographic factors. Soil properties were more important than topographic variables for explaining the differential growth of among tree species in some parts of the Southern Appalachians with parent materials that differ from those in my study [22, 25].

An important part of this study was testing accuracy of the SAM model for predicting yellow-poplar site index based on LFI [9]. Although the SAM model had been developed for a much broader area of the Southern Appalachian

Mountains, site index for the 14 yellow-poplar stands in this study was estimated within a confidence interval of about 2.4 m for a new observation, which is probably adequate for many forest management purposes. Even though yellow-poplar in this study was present in three stands where LFI was lower than in the dataset used to develop the SAM model, the relationship was consistent between site index and LFI.

In summary, a measure of topography surrounding the sampled stands, quantified by the landform index, accounted for significant variation in site index of two mesophytic tree species in a mountainous region of the Southern Appalachians. The higher site index of stands with larger values of LFI was likely caused by favorable environmental factors affecting soil moisture and fertility that may be associated with large concave landforms [26]. A definitive explanation for the growth response of trees to complex environmental relationships in forest stands will likely be difficult to obtain for reasons summarized by Jarvis and McNaughton [27]. As Peet [28] suggests, "…no simple measure is available which incorporates all the important components of site moisture."

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