Preliminary Evaluation of Environmental Variables Affecting Diameter Growth of Individual Hardwoods in the Southern Appalachian Mountains

W. Henry McNab
F. Thomas Lloyd

Abstract—The value of environmental variables as measures of site quality for individual tree growth models was determined for 12 common species of eastern hardwoods in the Southern Appalachian Mountains. Periodic diameter increment was modeled as a function of size, competition and environmental variables for 1,381 trees in even-aged stands of mixed-species. Resulting species models explained from 46 to 78 percent of total variation in diameter increment, of which environment accounted for 3 to 17 percent of the total explained. In similar model formulations where site index replaced environmental variables, it accounted for only 0.01 to 3.6 percent of variation. An important finding was the significant relationship of growing season length and precipitation with diameter increment. Results of testing a selected model with an independent data set indicate that environmental variables are useful as measures of site quality.

Introduction

A primary responsibility of silviculturists is forest management, and growth and yield models help them fulfill this responsibility. Researchers are seeking ways to improve the reliability of these models, increase the use of ecosystem classification and management, and ensure silviculturists have the best possible tools. The research described in this paper is aimed at improving the southern silviculturist's ability to manage forests effectively and efficiently.

Site index, the average total stand height at a particular reference age, is among the most widely used measures of site quality in growth and yield models of forest productivity (Carmean 1975). Although site index is often difficult to determine accurately because the underlying assumptions are seldom satisfied (Beck and Trousdell 1973), it accounts for significant variation in growth models for some species, particularly those that form relatively pure stands such as yellow-poplar (*Liriodendron tulipifera*) (Beck and Della-Bianca 1972). In stands of mixed species, however, site index may be insignificant (Bowling and others 1989; Harrison and others 1986). Replacing site index with environmental variables in diameter growth models would provide at least four advantages. First, errors associated with its measurement would be overcome (Lloyd and Hafley 1977). Second, an ecological basis for classification of site productivity would be provided (Barnes and others 1982; Reed 1980). Third, the application of models using geographic information systems would be facilitated (Teck and others 1996). Fourth, radial increment might be more sensitive than tree height to variation in site quality (Tryon and others 1957).

Environmental variables already used to quantify site quality for western conifers (Wykoff 1990) provide the basic model formulations for a national system of growth and yield models that comprise the Forest Vegetation Simulator (Tech and others 1996). Results of recent studies in the Southern Appalachian Mountains indicate that species composition is strongly related to environmental variables, particularly those associated with moisture gradients (McNab 1991). These results also suggest that environmental variables might be used to quantify site quality in growth models of the Southern Appalachian Mountains, where hardwood stands typically consist of multiple species (Beck 1981).

Our primary objective was to determine if environmental variables account for significant variation of periodic diameter growth of individual trees in multispecies hardwood stands in the Southern Appalachian Mountains. A secondary objective was to compare models based on environment with those using site index. The appropriate model formulation, we hypothesized, was the one developed for growth of individual conifers in the Rocky Mountains (Wykoff 1990). This study is part of an ongoing program of research to model the composition and dynamics of Southern Appalachian forests.

Methods

Study Area and Field Data

Tree growth data were obtained from sites in the Southern Appalachian Mountains in two regional-scale ecological units (Bailey and others 1994)— Blue Ridge Mountains (M221D) and Northern Ridge and Valley (M221A). Sixty-six permanent sample plots ranging from 0.15 to 0.25 acres were established in 1974 (Harrison and others 1986), on productive sites in relatively undisturbed, even-aged stands of multiple hardwood species. Sixty-two of these plots were thinned to favor trees of better quality, higher vigor, and

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W. Henry McNab is a Research Forester, and F. Thomas Lloyd is a Research Forester, USDA Forest Service, 1577 Brevard Road, Asheville, NC 28806.

desired species. Trees on each plot were numbered, identified by species, and measured for diameter at breast height (d.b.h.). Each tree was remeasured after 5 years to determine periodic d.b.h. increment. Oak (*Quercus* spp.) site index was determined for each plot with the equation developed by Olson (1959) and standardized for all plots by converting it to an equivalent value for white oak (*Q. alba*) using the relationships developed by Doolittle (1958).

Plots were characterized by a number of continuous and discrete variables associated with site quality based on Wykoff's (1990) formulation. We used ecological units because they are similar in concept to the location variable used by Wykoff (1990). Values of summer precipitation and frost-free days, obtained from isopleths (U.S. Department of Agriculture 1941), represented quantitative environmental variables of regional extent. Topographic variables determined on each plot included elevation to nearest 100 ft, aspect to nearest degree, slope gradient to nearest percent, and position on the slope in two classes: (1) lower or (2) middle and upper. The influence of aspect and slope gradient was quantified using the transformations suggested by Stage (1976).

Model Development and Data Analysis

Relationships among individual tree basal area increment and topographic variables were determined using multiple regression to evaluate the formulation (Wykoff 1990) that relates individual tree diameter growth to three components:

Diameter growth = tree size + competition + environment

The dependent variable (diameter growth) was quantified by radial increment and was transformed to the natural logarithm of 5-year periodic change in squared diameter outside bark at breast height (ln(dds)). Variation in diameter at the beginning of the growth interval attributable to size was accounted for by two functions of d.b.h. (also used by Wykoff 1990):

$$\text{Size} = b_0 + b_1{*}\ln(\text{d.b.h.}) + b_2{*}\text{d.b.h.}^2$$

where

ln(d.b.h.) = natural logarithm of initial d.b.h. (inches)
d.b.h.^{2} = initial d.b.h. squared, and
b_0, b_1, b_2 = regression coefficients

We quantified the effect of competition from neighboring trees on increment with stand basal area at time of thinning:

$$\text{Competition} = b_3{*}\text{BA}$$

where

BA = plot total stand basal area (ft/acre), and
b_3 = regression coefficient

Harrison and others (1986) found that stand basal area was the most important influence on periodic annual individual tree basal area increment for all species.

We quantified the influence of site factors on tree growth using the elevation and topographic variables of each plot. The following formulation is similar to that used by Wykoff (1990):

Environmental effects =

$$b_4{*}\text{ELE} + b_5{*}\text{ELE}^2 + b_6{*}\text{GRA}{*}(\sin(\text{ASP})) + b_7{*}\text{GRA}{*}(\cos(\text{ASP})) + b_8{*}\text{GRA} + b_9{*}\text{GRA}^2 + b_{10}{*}\text{PCP} + b_{11}{*}\text{FFD} + b_{12}{*}\text{SP} + b_{13}{*}\text{EU}$$

where

ELE = elevation (feet)
ELE ^{2}= elevation squared
ASP = aspect (degrees)
GRA = slope gradient (percent)
GRA^2= slope gradient squared
PCP = precipitation during warm season (inches)
FFD = frost free days (number)
SP = slope position (upper and middle or lower)
EU = ecological unit (M221A or M221D)
b_4 through b_{11} = regression coefficients.

Models were developed with stepwise multiple regression (SAS Institute Inc. 1985) using backward elimination of insignificant variables to minimize effects of multicollinearity (Zar 1996). The three variables accounting for size and competition (ln(d.b.h.), d.b.h.^{2}, basal area) were forced in the model. Effects of multicollinearity on significance of environmental variables were evaluated using Mallow's C_p statistic (Zar 1996).

Model Validation

The model developed for yellow-poplar was validated with data collected from 3,353 trees on 138, 0.25-acre permanent plots installed throughout the Southern Appalachians in 1961 and remeasured in 1966 to predict growth and yield of yellow-poplar (Beck and Della-Bianca 1972). The model development and validation data sets were similar except that 21 plots (607 trees) of the latter were in central Virginia, beyond the range of the developmental data set. The ranges of diameter growth, size, competition, and environmental site variables in each data set were comparable. The design of the yellow-poplar study was similar to that of the mixed hardwood species. Values of independent variables were calculated for size, competition, and site effects, and the model was solved to obtain predicted ln(dds). Residuals were plotted against and correlated with d.b.h. and site index to determine model performance over a range of sizes and the adequacy of environmental variables in the model.

Comparison With Site Index

A second set of models used site index to account for variation in diameter growth associated with site quality. Variables accounting for effects of size and competition were not changed:

Diameter growth =

$$b_0 + b_1{*}\ln(\text{d.b.h.}) + b_2{*}(\text{d.b.h.}^2) + b_3{*}(\text{BA}) + b_4{*}(\text{site index})$$

All variables were forced into the model for this comparison.

Results and Discussion

Model Development

A total of 1,381 trees were sampled and combined into the 12 species and groups of species recognized by Harrison and others (1986) (table 1). Species of magnolia (*Magnolia* sp.) and birch (*Betula* sp.) occurred infrequently and were grouped by genera. A miscellaneous group consisted of nine species present in numbers too few for model development. Hereafter, both species and species groups are referred to as species.

Chestnut oak (*Q. prinus*) and northern red oak (*Q. rubra*) were the best represented in the data set; magnolia and black locust (*Robinia pseudoacacia*) were least represented. Five species typically occur on middle to lower slopes or in coves and are considered mesophytic: black cherry (*Prunus serotina*), northern red oak, yellow-poplar, magnolia, and birch. Scarlet oak (*Q. coccinea*) and black oak (*Q. velutina*) are considered xerophytic and generally occur on middle to upper slopes and ridges. Red maple (*Acer rubrum*) and white oak are common on both moist and dry sites. Black cherry and northern red oak occur more commonly at higher elevations (>3,000 ft) and white and black oaks are more prevalent at lower elevations (<3,000 ft). Species in this study are common constituents of predominant forest cover types of the Southern Appalachians below about 4,500 ft, especially the types identified by the Society of American Foresters (Eyre 1980) as chestnut oak, white oak-black oak-northern red oak, yellow-poplar-white oak-northern red oak, and sugar maple-beech-yellow birch. Most species sampled are moderately tolerant to intolerant of shade.

Table 1—Common name, scientific name, abbreviation, and number of trees sampled for each species or group of species.

Species	Genus and species	N
Black cherry	*Prunus serotina* Ehrh.	70
Northern red oak	*Quercus rubra* L.	214
White oak	*Quercus alba* L.	151
Yellow-poplar	*Liriodendron tulipifera* L.	146
Black oak	*Quercus velutina* Lam.	56
Magnolia[a]	*Magnolia* spp.	42
Black locust	*Robinia pseudoacacia* L.	44
Birch[b]	Betula spp.	189
Chestnut oak	*Quercus prinus* L.	222
Scarlet oak	*Quercus* coccinea Muenchh.	58
Red maple	*Acer rubrum* L.	130
Miscellaneous[c]	Various species	59

[a] Consisted of Frasers (*M. fraserii* Walt.) and wahoo (*M. acuminata* L.).

[b] Consisted of sweet (*B. lenta* L.) and yellow (*B. allegheniensis* Britton).

[c] Consisted of basswood (*Tilia heterophylla* Vent.), beech (*Fagus grandifolia* Ehrh.), blackgum (*Nyssa sylvatica* Marsh.), hickory (*Carya* spp.), mountain silverbell (*Halesia monticola* Sarg.), sassafras (*Sassafras albidum* (Nutt.)Nees), sourwood (*Oxydendrum arboreum* (L.)DC.), sugar maple (*A. saccharrum* Marsh.), and white ash (*Fraximus americana* L.).

Mean values of diameter growth were only slightly greater for mesophytic species than for xerophytic (table 2). Mean d.b.h. was greatest for yellow-poplar and least for birches. Residual stand basal area after thinning ranged from 28.3 to 106.6 ft^2/acre and averaged from 58 to 72 ft^2/acre. Mean elevation of most species was about 3,300 ft. Slope gradient varied most among the site components: precipitation and frost-free days varied little among species. Graphical examination of plot frequency in relation to aspect indicated that species were represented on sites of all azimuths.

The tree size variables, ln (d.b.h.) and d.b.h.^{2}, were consistently highly correlated ($p < 0.0001$) with increment for all species except the miscellaneous group (table 3). The correlation of competition (stand basal area) and diameter growth was variable among species. Elevation was significant ($p < 0.01$) for three species. Aspect was strongly correlated ($p < 0.001$) with growth of only the miscellaneous species. Gradient was strongly correlated ($p < 0.001$) with growth for two species. Precipitation was significantly negatively correlated ($p = 0.01$) with scarlet oak. The number of

Table 2—Mean (+/-s.d.[a]) individual tree diameter growth (ln(dds)), size (d.b.h.), competition (basal area) and environmental site characteristics by species[b].

Variable	BC	NRO	WO	Y-P	BO	M	BL	B	CO	SO	RM	MISC
Ln(dds)	3.1	2.9	2.4	3.2	2.8	3.0	2.1	2.2	2.4	2.9	2.7	2.2
(in.)	±0.7	±0.6	±0.8	±0.6	±0.6	±0.6	±0.8	±0.7	±0.7	±0.7	±0.6	±0.8
D.b.h.	8.1	9.7	10.2	11.4	11.3	9.9	8.0	6.8	8.5	9.6	8.0	7.1
(in.)	±3.1	±2.9	±2.5	±2.9	±2.1	±3.0	±2.6	±2.1	±2.1	±2.9	±2.1	±3.0
Basal area[c]	61	62	69	69	62	58	67	70	64	59	72	64
(ft^2/ac)	±21	±19	±23	±20	±23	±18	±10	±20	±19	±19	±17	±23
Elevation	4215	3221	2466	3080	2643	3434	3462	3835	3105	2935	3330	3469
(feet)	±386	±667	±346	±711	±411	±630	±455	±732	±671	±475	±668	±748
Gradient	42	38	22	31	34	38	42	40	29	36	30	38
(percent)	±17	±19	±10	±17	±13	±13	±16	±14	±15	±11	±17	±17
Precipitation	29	27	25	26	26	25	28	26	26	26	27	28
(inches)	±2	±3	±2	±3	±3	±2	±2	±3	±3	±3	±4	±3
Frost free	172	177	177	178	180	174	178	169	176	181	171	177
(days)	±5	±8	±7	±7	±4	±9	±6	±9	±9	±5	±10	±5

[a] s.d. = standard deviation.

[b] BC = black cherry, NRO = northern red oak, WO = white oak, Y-P = yellow-poplar, BO = black oak, M = magnolia, BL = black locust, B = birch, CO = chestnut oak, SO = scarlet oak, RM = red maple, MISC = miscellaneous species.

[c] Basal area of the stand in which the species occurred.

frost-free days was correlated ($p < 0.001$) with the growth of six species. Among species, black oak growth was not significantly correlated with any environmental variables and black locust was correlated with most variables.

Size and competition variables were forced into parsimonious models for species (table 4). In the presence of other variables, the size variable (d.b.h.^{2}) was significant for only three species. The competition variable, basal area, accounted for significant variation in all species except magnolia. Other variables included in the best models of species ranged from three to nine variables (including the intercept). More than half of the models for species included either precipitation or growing season length. Multiple correlation coefficients (R^2) for the models ranged from 0.46 for

Table 3—Correlation coefficients of individual tree diameter growth (ln(dds)) with tree size (ln(d.b.h.), d.b.h.^{2}), competition (basal area), and environmental site variables by species[a].

Variable	BC	NRO	WO	Y-P	BO	M	BL	B	CO	SO	RM	MISC
Ln(d.b.h.)	0.63	0.71	0.69	0.62	0.51	0.57	0.65	0.54	0.50	0.80	0.59	0.38
(inches)	***	***	***	***	***	***	***	***	***	***	***	***
d.b.h.^{2}	0.57	0.69	0.61	0.60	0.49	0.61	0.64	0.48	0.53	0.75	0.53	0.26
(inches)	***	***	***	***	***	***	***	***	***	***	***	*
Basal area	–0.20	0.06	–0.47	–0.42	–0.31	–0.03	0.03	–0.29	–0.41	–0.06	–0.20	–0.07
(ft^2/ac)	*	ns	***	***	**	ns	ns	***	***	ns	*	ns
Elevation	0.04	–0.07	0.21	0.01	0.04	–0.36	0.49	–0.04	0.13	–0.26	0.20	–0.10
(ft)	ns	ns	**	ns	ns	**	***	ns	*	*	*	ns
Sine aspect	0.20	–0.11	0.17	0.25	0.05	–0.01	–0.40	0.14	0.05	–0.18	0.16	0.40
(degrees)	*	*	*	**	ns	ns	**	*	ns	ns	*	***
Cosine aspect	–0.24	–0.11	–0.11	0.02	0.16	0.22	–0.30	0.00	–0.15	–0.18	–0.13	0.05
(degrees)	*	*	ns	ns	ns	ns	*	ns	*	ns	ns	ns
Gradient	0.04	–0.18	–0.02	0.38	–0.03	–0.20	0.29	0.09	0.29	–0.12	0.11	0.07
(percent)	ns	**	ns	***	ns	ns	*	ns	***	ns	ns	ns
Precipitation	0.28	–0.04	0.14	0.06	0.06	–0.09	0.03	0.05	0.06	–0.31	–0.03	0.13
(inches)	*	ns	*	ns	ns	ns	ns	ns	ns	**	ns	ns
Frost free days	0.36	0.01	0.24	0.24	0.07	0.29	–0.25	0.27	0.34	0.13	–0.13	0.42
(no)	***	ns	***	***	ns	*	*	***	***	ns	ns	***

[a] Asterisks under each coefficient indicate level of significance: 1 = 0.1, 2 = 0.01, 3 = <0.001, ns = not significant.

[b] BC = black cherry, NRO = northern red oak, WO = white oak, Y-P = yellow-poplar, BO = black oak, M = magnolia, BL = black locust, B = birch, CO = chestnut oak, SO = scarlet oak, RM = red maple, MISC = miscellaneous species.

Table 4—Parsimonious regression models for each species[a] with overall multiple correlation coefficient (R^2) and measure of multicollinearity [C_p]. (Asterisks under each species indicate level of significance of the variable[b].) (The first four variables were forced into the models.)

Variable	BC	NRO	WO	Y-P	BO	M	BL	B	CO	SO	RM	MISC
Intercept	**	*	ns	**	*	ns	ns	***	***	**	***	*
Ln(d.b.h.)	***	***	***	**	*	ns	ns	***	***	***	**	***
d.b.h.^{2}	ns	ns	***	ns	ns	ns	ns	*	ns	ns	ns	*
Basal area	***	***	***	***	*	ns	*	***	***	**	***	*
Elevation	ns	ns	*	ns	ns	ns	ns	ns	ns	*	**	ns
Elevation^2	***	***	*	ns	ns	ns	*	***	ns	*	**	ns
Sine aspect	ns	ns	ns	ns	*	ns	ns	*	***	ns	ns	ns
Cosine aspect	ns	ns	ns	ns	ns	ns	ns	**	*	**	**	ns
Gradient	ns	*	ns	***	*	ns	ns	ns	***	ns	ns	ns
Gradient^2	*	*	ns	ns	*	ns	ns	ns	***	*	**	***
Precipitation	*	ns	*	ns	ns	ns	ns	**	*	**	*	ns
Frost free days	**	ns	ns	***	ns	*	ns	**	ns	ns	*	ns
Eco. unit	ns	ns	ns	ns	ns	*	ns	ns	*	ns	ns	ns
Slope position	ns	*	ns	***	*	ns	ns	ns	*	ns	ns	ns
N in model	8	8	7	7	8	6	5	9	11	9	10	5
C_p	7.1	8.0	0.4	6.9	10.0	2.0	3.9	6.2	7.8	4.5	7.5	1.7
R^2	0.75	0.59	0.67	0.66	0.51	0.49	0.54	0.62	0.60	0.78	0.59	0.46

[a] BC = black cherry, NRO = northern red oak, WO = white oak, Y-P = yellow-poplar, BO = black oak, M = magnolia, BL = black locust, B = birch, CO = chestnut oak, SO = scarlet oak, RM = red maple, MISC = miscellaneous species.

[b] 1 = 0.1, 2 = 0.01, 3 = <0.001, ns = not significant.

the miscellaneous group to 0.78 for scarlet oak. Values of C_p were less than or equal to the number of variables in the model for all species except black oak, indicating that most models are probably adequately precise and have acceptable levels of multicollinearity (Zar 1996).

Figure 1 displays the relative importance of the three types of variables (size, competition, and environmental site effects) in explaining variation in growth by species. Almost 60 percent of the variation was explained for all species; almost 80 percent for scarlet oak. For most species, the effect of tree size accounted for as much variation as competition and environment variables combined. The effect of competition was least important for the magnolias and northern red oak but was very important for black cherry and chestnut oak. Environment variables explained relatively little variation in d.b.h. growth of white oak but accounted for more than 8 percent of variation for other species.

The model developed for yellow-poplar, typical of those for other species, was examined in more detail using an independent data set. The final model for yellow-poplar was based on 146 trees and consisted of seven significant variables (including the intercept). All variables except d.b.h.^{2} were highly significant ($p < 0.01$) Signs of the coefficients were biologically logical for all variables except frost-free days. The negative sign of this variable indicates that radial growth is reduced as the number of frost free days increases. In addition, the simple correlation coefficient was positive, suggesting the presence of multicollinearity.

Residuals of the yellow-poplar regression exhibited no pattern and, except for a single tree (indicated by arrow), were uniformly distributed about the zero reference line (fig. 2). The subject tree grew only 0.2 inches during the 5-year period and was considered for exclusion as an outlier. Trees of similar size and crown class grew an average of 0.6 in. There was no indication of damage, disease, or injury that might explain its slow growth. In subsequent inventories this tree also grew much less than its cohorts on the same plot, which tends to exclude measurement error as the source of variation. Trial omission of this tree improved R^2 of the final model by 3 percent, but resulted in the same set of significant variables and no change in distribution of residuals. The subject tree was retained in the data set because it probably represented other trees in the validation data set. Larger data sets (for example, Wykoff 1990) probably included a number of trees with less than average diameter increment. The residuals of this model were not correlated with site index ($r = 0.02$, $p < 0.78$).

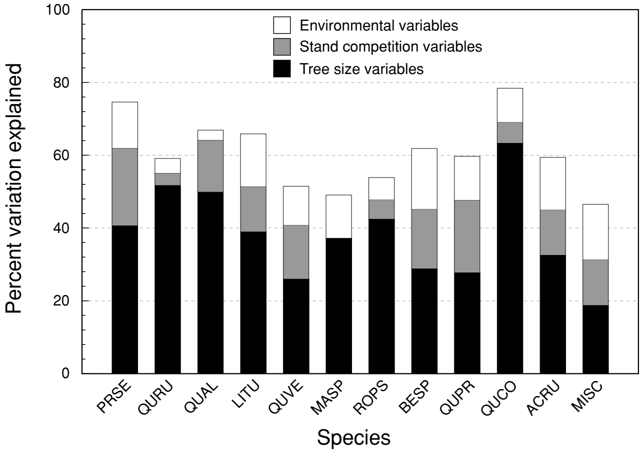

Figure 1—Proportion of total variation explained by variables of size, competition, and environment for the best prediction model for each species.

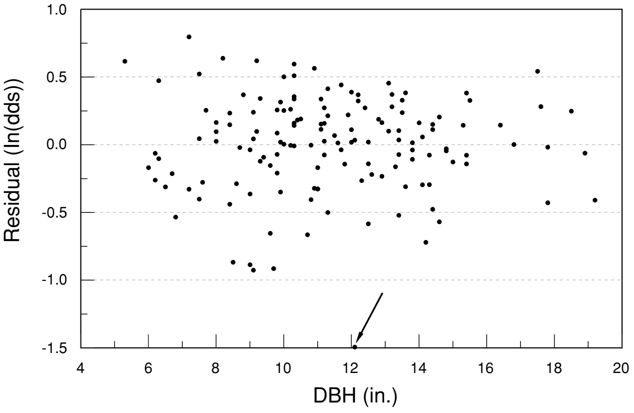

Figure 2—Residuals of the yellow-poplar model developed, using 151 trees. The tree identified by the arrow is explained in the text.

Comparison With Northern Rocky Mountains Model

Models developed for Southern Appalachian Mountain species were more variable in formulation than those developed for the Northern Rocky Mountains by Wykoff (1990). Similar to western conifers, size and competition significantly affect diameter increment of eastern hardwoods. Elevation was a component in models of all western conifers (Wykoff 1990), but was significant for only three hardwood species (black cherry, northern red oak, and birch), which generally occur at higher elevations. Similarly, aspect and gradient were present in all western conifer models, but were moderately significant ($p < 0.01$) for only half of the eastern hardwood species. Ike and Huppuch (1968) reported that formulation of site quality models for Appalachian hardwoods varied by hardwood species, particularly among species of oaks. Generally, the overall effect of topographic variables was inconsistent for explaining variation of ln(dds) among species.

The association of individual tree diameter growth with precipitation and length of growing season for several species in our study suggests the importance of broad-scale environmental variables. Tryon and others (1957) reported that diameter growth of yellow-poplar was influenced by precipitation and temperature in West Virginia. Overall lack of significance of the two mapped ecological units suggests that tree growth may be more sensitive to individual environmental components than to combined components. When precipitation and growing season length were removed, ecological unit became significant ($p = 0.03$) only for scarlet oak. Our results generally agree with those of Wykoff (1990), who found discrete variables were necessary to account for unmeasured regional climatic and geologic effects on tree increment.

Validation of the Yellow-Poplar Model

We tested the yellow-poplar model by predicting 5-year diameter growth of 3,353 trees in a validation data set. The distribution of residuals (fig. 3) was homogeneous and poorly correlated with d.b.h. ($r = -0.03$) although the relationship was significant ($p < 0.05$) because the sample size was large. Residuals were significantly correlated with site index ($r = 0.27$, $p < 0.0001$). The bias in our model suggests that additional variables should be included in the model. Using additional variables associated with competition, Wykoff (1990) found no correlation of residuals with site index in models for Northern Rocky Mountain conifers. Additional factors that may contribute to the bias in our model include: (1) different behavior of yellow-poplar diameter growth in mixed-species stands compared to pure stands; (2) climatic differences during the first 5 years after treatment (1961–1966) of the validation plots compared to that on the developmental plots (1974–1979); and (3) extending the model into central Virginia, beyond its range of applicability.

Comparison With Site Index

Compared to models based on environmental variables, models based on site index performed less satisfactorily (fig. 4). Site index accounted for relatively small proportions of variation in diameter growth for all species (not displayed), from about 3 percent for magnolia and chestnut oak to less than 0.01 percent for northern red and scarlet oaks. For yellow-poplar, site index accounted for 0.2 percent of the variation in diameter increment. The species in which the proportion of variation explained by site index was nearest to that of the model based on environmental variables was white oak, the only species that was not converted to a common basis.

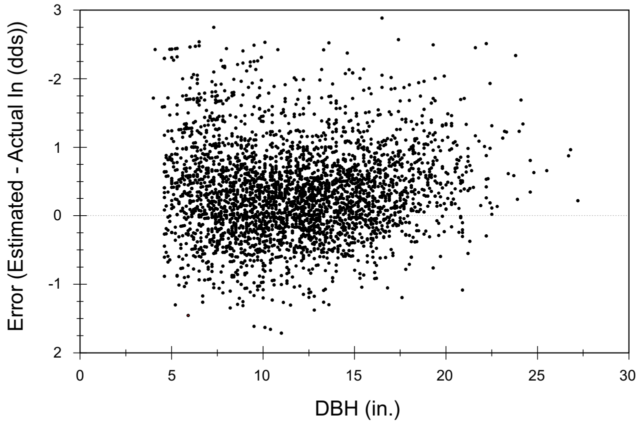

Figure 3—Residuals for the yellow-poplar model validated using an independent data set of 3,353 trees.

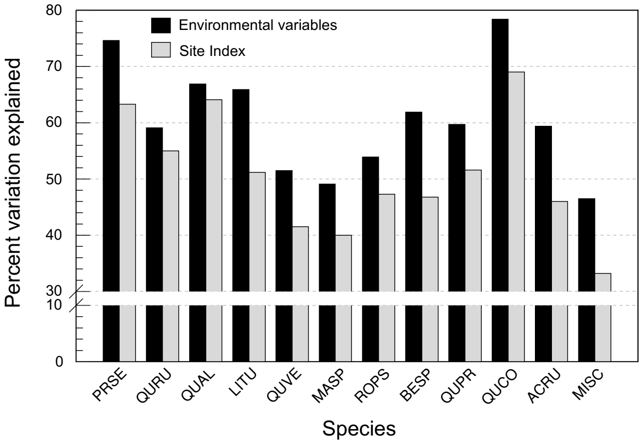

Figure 4—Proportion of total variation in diameter increment explained by models based on environmental variables and site index (size and competition variables included in each model) for the best prediction equation of each species.

Several explanations are possible for the poor performance of site index in the model formulation: (1) conversion of site indexes for all species to that of white oak introduced unknown errors (Lloyd and Hafley 1977); (2) site index relationships are based on prediction equations, which may be biased (Beck and Trousdell 1973); and (3) radial increment might be a more sensitive than height increment to changes in environmental influences (Tryon and others 1957).

Conclusions

Results of this preliminary study suggest that site index can be replaced by environmental variables in growth models of mixed species in the Southern Appalachian Mountains. Our analysis suggested that diameter growth of each species responds individually to environment and that no single environmental variable was of primary importance. The relative importance of two variables on diameter growth-precipitation and length of growing season-should be investigated further. Evaluation of model formulation should continue, and additional competition variables, such as basal area greater than the subject tree and crown ratio, should be included. Our test suggests that the Forest Vegetation Simulator formulation for the Northern Rocky Mountains is applicable to hardwoods in the Southern Appalachians.

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