ASSESSING AGE- AND SITE INDEX-INDEPENDENT DIAMETER GROWTH MODELS OF INDIVIDUAL-TREE SOUTHERN APPALACHIAN HARDWOODS

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ABSTRACT. Models of forest vegetation dynamics based on characteristics of individual trees are more suitable to predicting growth of multiple species and age classes than those based on stands. The objective of this study was to assess age- and site index-independent relationships between periodic diameter increment and tree and site effects for 11 major hardwood tree species. Model formulations of western conifers were evaluated by multiple regression for significance of three types of variables affecting diameter growth: tree size, competition, and site effects. Many variables were highly correlated with diameter growth but were also intercorrelated. Importance of size or competition variables differed by species and parsimonious models of highly significant (p<0.01) variables explained an average of 60% of the total variation associated with diameter increment. One or two topographic or geographic site-effect variables were significant in models for seven species. but accounted for little (<5%) variation. Detailed evaluation of a yellow-poplar (*Liriodendron tulipifera*) model indicated prediction errors were not correlated with tree size. stand age, or site index. Validation testing of the yellow-poplar model with independent data suggested prediction errors were uniformly distributed, but strongly biased. Unexplained bias was associated mostly with tree size. The formulation of diameter growth models for western conifer species is appropriate for eastern hardwoods. but reasons for the unexplained bias should be addressed.

KEYWORDS: Accuracy, bias. competition, deciduous trees. diameter growth models. height-diameter relationships. validation.

1 INTRODUCTION

Deciduous, unmanaged forest stands of the eastern United States typically consist of multiple species of trees (Braun 1950) that are not even-aged (Beck 1981). Modeling growth of stands with these characteristics is facilitated by using individual tree models (Shifley 1987, Wykoff 1990) that do not use age or site index (Huang and Titus 1993). Individual tree models are available for major species of eastern hardwoods (Harrison and others 1986, Shifley 1987), but most models depend on even-aged stands or use site index. Age and site index-independent models have been developed for major individual species of western conifers (Wykoff 1990). These models account for three principal types of variation affecting tree diameter growth: size of the individual tree, competition experienced, and environmental effects (i.e. site quality). Similar models developed for principal hardwood species of the Southern Appalachian Mountains would aid in the implementation of the Forest Vegetation Simulator, a national system of timber stand development models (Teck and others 1996).

In a preliminary, exploratory investigation (McNab and Lloyd, In press), we used the formulations for western conifers (Wykoff 1990) to investigate the relationship of diameter growth to individual tree size and site effects. We found that topographic variables were superior to site index in models of individual tree growth for 11 major hardwood species. However, validation testing of a model developed for yellow-poplar (*Liriodendron tulipifera*) revealed that the model was slightly biased. Excluded from that study were other variables associated with tree effects, within-stand competition

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and other site effects, geographic location effects, and geologic effects. Favorable results from our preliminary study suggest that we evaluate the fully formulated Wykoff (1990) model for major hardwood arborescent species of the Southern Appalachian Mountains.

This paper presents the results of our exploratory study of the completely formulated Wykoff (1990) model applied to Southern Appalachian hardwoods. Our previous study focused on the feasibility of replacing site index in diameter growth models with common topographic variables. In this investigation, we extended the scope of the relationship found in the previous study (McNab and Lloyd, In press) by including variables that account for competition and other site effects. We used correlation and regression analyses to address three questions: What was the relative importance of size, competition, and site effects on diameter growth of individual trees? Could parsimonious formulations be developed that accounted for much of the variation in diameter growth of individual trees? Were the models accurate when evaluated with an independent data set? We did not present coefficients for our models because this study was primarily an assessment of possible model formulations. We demonstrated and concluded in this study that: (1) the dependent variable (periodic change in squared diameter) was well behaved in growth models and was significantly correlated with tree size (functions of diameter), competition (functions of basal area) and some site effects (measures of environmental conditions), (2) parsimonious models that included significant variables of tree size and competition, but few site effects, were developed that explained an average of 60 percent of the variation in periodic change in squared diameter, and (3) validation testing of a parsimonious model for yellow-poplar with independent data suggested an appropriate form of the model but revealed an unexplained source of bias associated mainly with tree site.

2   DATA, MODELS, AND METHODS

2.1 Field Data and Study Area. The analysis data set came from 62 permanent sample plots at 10 principal locations throughout the Southern Appalachian Mountains (Fig. 1). The plots were established in 1974 in relatively undisturbed, even-aged stands of multiple hardwood species on mesic to submesic sites of better than average productivity. The 0.06-ha to 0.1-ha plots were situated in clusters of three to eight at each location for the primary purpose of investigating the growth and yield response of hardwoods to thinning. Each plot was thinned to a specified residual basal area from below (removal of suppressed and intermediate crown classes) to favor trees of larger size, better than average quality, high vigor, and commercially desirable species. Residual trees on each plot were numbered, identified by species, and measured for diameter at breast height (DBH) (1.37m above ground level). A systematic sample of trees on each plot was measured for height to base of the live crown and to the tip. Each tree was measured again after five years to determine periodic DBH increment. We used the same data that Harrison and others (1986) used to develop primarily age-dependent individual tree basal area increment equations for the same species and species groups (Table 1).

2.2 Model formulation variables. We hypothesized that an appropriate initial model formulation for eastern hardwoods followed that developed for diameter growth of individual conifers in the Rocky Mountains (Wykoff 1990). We used multiple regression to express tree growth in relation to three primary types of variation:

Diameter growth = function of (size effects + competition effects + site effects)   (1)
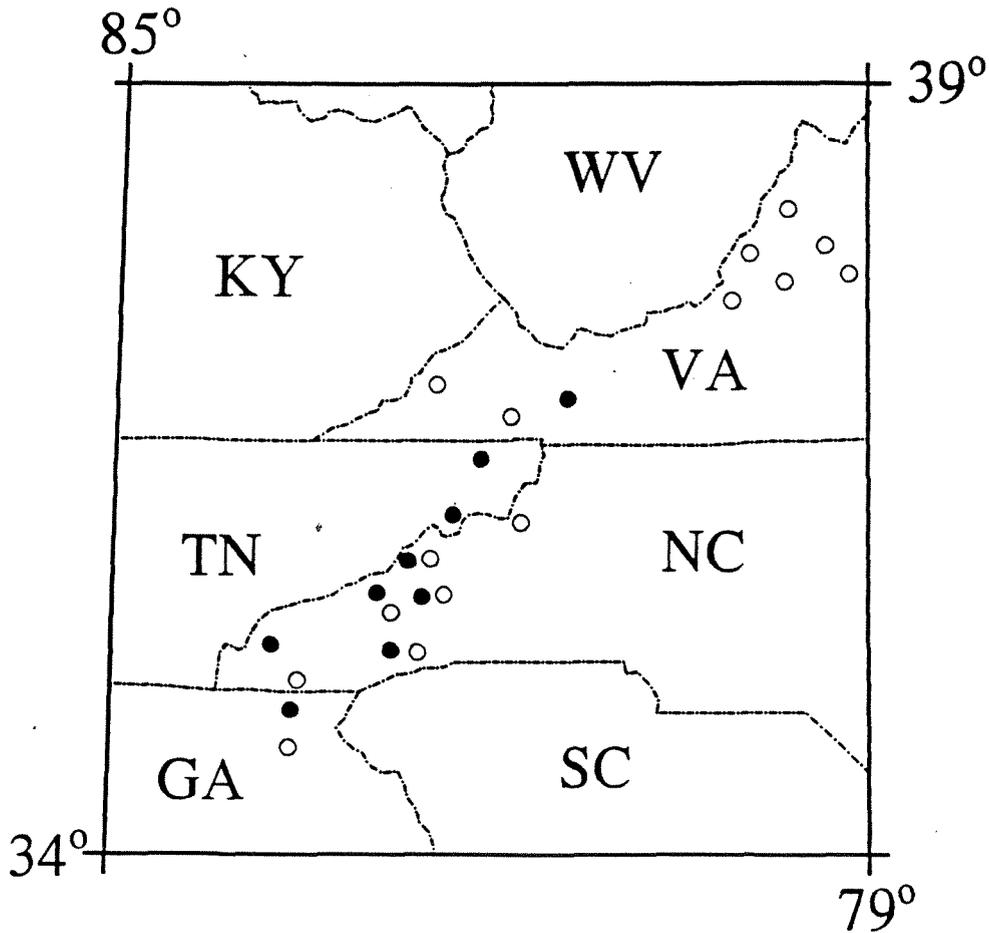
85° 39°

WV

KY

VA

TN NC

GA SC

34° 79°

Figure 1: General location of sample plots used for analysis (●) and validation (○) within the southern Appalachian Mountains.

The dependent response variable (diameter growth) was quantified and transformed by calculating the natural logarithm of five-year periodic change in squared difference in diameter at breast height (ln(DDS)), as described by Wykoff (1990). Shifley (1987) tested this and several other dependent variables for predicting radial growth of eastern hardwoods and found little difference among them. We substituted DBH outside bark for DBH inside bark because we lacked specific conversion functions to accurately estimate inside bark diameter by species.

2.3 Tree size effects. Effects of tree size on diameter growth are quantified by transformations of DBH. We formulated the response of the independent variable, diameter growth (ln(DDS), to tree size as:

$$\ln(DDS) = b_0 + b_1[\ln(DBH1)] + b_2(DBH1^2) \qquad (2)$$

where $\ln(DBH1)$ = natural logarithm of initial DBH (cm), $DBH1^2$ = initial DBH squared (cm^2), and b_0-b_2 = regression coefficients.

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Table 1: Species and sample size from plots in the Southern Appalachian Mountains used in this study and by Harrison and others (1986).

Arborescent species	Genus and species[b]	Plots[a]	Trees	Age in model[b]	R[2c]
Black cherry	*Prunus serotina* Ehrh.	15	70	Yes	0.77
Northern red oak	*Quercus rubra* L.	48	214	No	0.61
White oak	*Quercus alba* L.	28	151	Yes	0.56
Yellow-poplar	*Liriodendron tulipifera* L.	43	146	Yes	0.67
Black oak	*Quercus velutina* Lam.	26	56	Yes	0.59
Magnolia[d]	*Magnolia* spp.	16	42	Yes	0.63
Black locust	*Robinia pseudoacacia* L.	17	44	Yes	0.74
Birch[e]	*Betula* spp.	25	189	Yes	0.45
Chestnut oak	*Quercus prinus* L.	36	222	Yes	0.56
Scarlet oak	*Quercus coccinea* Muenchh.	17	58	No	0.74
Red maple	*Acer rubrum* L.	26	130	No	0.41
Miscellaneous[f]	Various species	25	59	Yes	0.41

[a]Total plots = 62.

[b]Stand age included as a variable in models developed by Harrison and others (1986).

[c]Correlation coeffients reported for models developed by Harrison and others (1986).

[d]Consisted of cucumbertree (*M. acuminata* L.) and Fraser magnolia (*M. fraserii* Walt.).

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

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

2.4 Competition effects. Effects of competition on diameter growth included variables that account for influence of neighboring trees on the subject tree or that may be a response to the number and size of nearby neighbors. We included two measures of competition used by Wykoff (1990) that we had omitted in the previous study: basal area larger than the subject tree and crown ratio. Two conventional measures—original stand basal area and proportion of the original stand basal area remaining after thinning—were also included as competition variables. We used the following formulation to account for variation in diameter increment as a function of tree size and competition:

$$\ln(DDS) = b_0 + \text{tree size} + b_3(BAL) + b_4(CR) + b_5(BA1) + b_6(BAR) \tag{3}$$

where BAL = interaction of basal area larger than the subject tree (m^2/ha) divided by $\ln(DBH1+1)$, CR = crown ratio (ratio of crown length to total tree height), BA1 = initial stand basal area after thinning (m^2/ha), BAR = basal area reduction (ratio of plot initial stand basal area to original basal area before thinning), and b_0-b_6 = regression coefficients.

The interaction term BAL was used without preliminary evaluation based on results presented by Wykoff (1990). The crown competition factor used by Wykoff (1990) was not included in our analysis because it was not available for the species in our analysis.

2.5 Site effects. Site effects are environmental variables primarily associated with the plot moisture regime that are indirectly expressed by topographic measures of elevation, aspect, and gradient. We supplemented previously used variables (McNab and Lloyd, In prep) by adding variables that accounted for the effects of landforms, geographic location, and geologic unit. Microscale and mesoscale landforms were quantified by terrain shape index (McNab 1989) and landform index (McNab 1993) of each plot, respectively. Effects of geographic location were quantified by latitude and longitude. The predominant geologic unit from which soils of the plot formed was accounted for by homogeneous areas of similar physiographic composition. The complete formulation is expressed as:

$$\ln(DDS) = b_0 + \text{tree size} + \text{competition} + b_7(ELEV) + b_8(TASP) + b_9(GRAD)$$
$$+ b_{10}(TSI) + b_{11}(LFI) + b_{12}(LAT) + b_{13}(LON) + b_{14}(GEO) \qquad (4)$$

where ELEV = elevation (m), TASP = transformed aspect using the cosine relationship of Beers and others (1966) (cosine of degrees azimuth), GRAD = slope gradient (percent), TSI = terrain shape index (no units), LFI = landform index (no units), LAT = latitude (decimal degrees), LON = longitude (decimal degrees), GEO= geologic unit (discrete rock formation), and b_7-b_{14} = regression coefficients. The two geographic variables included as site effects for expediency--LAT and LON--are indicative of regional climatic regimes. GEO was also included as a site effect to account for broad-scale properties of soils associated with rock types.

GEO's had been grouped into four major units according to their general location and composition Hatcher (1981) (Table 2). Analysis of variance was used for initial screening to determine whether GEO significantly (p• 0.05) affected ln(DDS). Significant geologic units were separated using Scheffe's test and included in the regression as one or more categorical variables (Zar 1996).

2.5 Model Development. The relationship between ln(DDS) and size, competition, and site effects was developed for each species using the stepwise multiple regression procedure implemented in the Statistical Analysis System software (SAS Institute, Inc 1985). The maximum R^2 improvement technique (MAXR) option of PROC STEPWISE was used to screen significant combinations of independent variables to determine their relative individual and collective importance in accounting for variation of ln(DDS). To help develop highly parsimonious equations with assumed reduced effects of multicollinearity resulting from correlated variables (particularly site effects), only those independent variables significant at the p=0.01 threshold level of probability were included in the model. In addition, no more than two uncorrelated environmental variables were allowed to enter a model (similar restrictions were not imposed on the size and competition components). Models were rendered biologically interpretable by requiring agreement of signs between simple correlations and variable coefficients and knowledge of response of trees to these components. Multiple coefficients of determination (R^2) were used to determine the percent of variation of ln(DDS) explained by significant independent variables in the model and to judge the relative value of including additional variables in model formulation. Mallows' C_p statistic was used to evaluate the likely effects of multicollinearity on model performance (i.e. in multiple regression models that do not suffer from under or over fitting, C_p will approximately equal the number of included parameters, including b_0) (Zar 1996).

Table 2: Sample sizes and characteristics of the four geologic units of plots in the Southern Appalachian Mountains.

Unit[a]	Trees	General location	Characteristics
1A	175	Ridge and Valley, and Cumberland Plateau	Sandstones, shales, limestones, and dolomites that weather into clayey and sandy soils.
2A	421	Basement rocks of the western Blue Ridge Mountains	Gneisses and associated intrusive igneous rocks that produce generally light colored soils sandy to clayey in texture.
2D	234	Low-elevation foothills of the western parts of the Blue Ridge Mountains	Metamorphosed sandstones and shales. Soils range from clayey to sandy.
3A	551	Eastern Blue Ridge Mountains and western Piedmont	Metasandstones interlayered with granitics, granitics, and meta volcanic rocks. Soils range from sandy to clayey in texture.

[a]Delineated by Hatcher (1981)

2.6 Model validation. Accuracy of the yellow-poplar model was tested with an independent validation data set from permanent plots (Fig. 1) established by Beck and Della-Bianca (1972) to study growth and yield of nearly pure stands in the Southern Appalachian Mountains. Yellow-poplar is a commercial mesophytic species that is moderately tolerant to intolerant of shade. It typically occurs as

the predominant (>75% basal area) species in generally even-aged stands and responds well in diameter growth to management activities, such as thinning. Design of the yellow-poplar study was similar to that used for the analysis data set. Individual tree initial DBH (DBH1) and total height (THT1) were collected from 967 trees on 141, 0.1-ha permanent plots installed in even-aged, relatively pure stands that had been thinned from below to varying levels of residual basal area in 1961. The trees were remeasured in 1966 to determine 5-year change of DBH (DBH2). The ranges of tree size, competition, and the significant site effects of the validation data set were constrained to values used for analysis and model development. Residuals of actual minus predicted values of ln(DDS) were plotted against and compared with DBH1, site index, and age to evaluate error and probable model performance. A test of conditional errors was used to determine whether similar regression formulations fitted to the two data sets estimated the same population (Zar 1996).

Measurement of actual diameter growth was used to evaluate predicted growth by the yellow-poplar model using scatter plotting and the microcomputer program DOSATEST (Wiant 1993). The DOSATEST program tests mean bias and precision of prediction equations and implements rationale for accuracy developed by Reynolds (1984), which was translated into computer code by Rauscher (1986). Bias, defined as the average error in predictions made by the model, was calculated as the mean difference between actual and predicted ln(DDS). Precision is the tolerance interval that delineates 95 percent confidence intervals for 95 percent of the errors.

3   RESULTS AND ANALYSES

A total of 1,379 trees were measured and combined into the 12 species groups recognized by Harrison and others (1986) (Table 1). Two groups, magnolia (*Magnolia sp.*) and birch (*Betula sp.*), each consisted of two species. Northern red oak (*Quercus rubra*) and yellow-poplar occurred on the greatest number of plots; black cherry (*Prunus serotina*) and magnolia on the fewest. Chestnut oak (*Q. prinus*) and northern red oak (*Q. rubra*) were the most represented in the data set; black locust (*Robinia pseudoacacia*) and magnolia were the least. We omitted the miscellaneous group from our study, which consisted of only 59 trees representing 9 species of widely differing silvical characteristics that were present in numbers too few for development of individual models.

Measures of tree size, competition, and site effects were relatively uniform among species (Table 3). Mean periodic five-year diameter increment was greatest for black cherry (3.7 cm), and least for white oak and black locust (1.5 cm). BA1 varied from 13.3 to 16.4 m²/ha. The BAR was greatest for stands in which birch and red maple (*Acer rubrum*) trees were present. ELEV and GRAD were greatest for plots with black cherry and lowest for those with white oak (*Q. alba*). Mean values of TSI indicated a generally linear to concave land surface shape for all plots except those on which black locust

Table 3: Mean (±1SD) of size effects, competition and site effects by species in the Southern Appalachian Mountains.

Variable	Species[a]									
	Prse	Quru	Qual	Litu	Quve	Masp	Rops	Besp	Qupr	Quco	Acru
DBH1	20.5	24.7	25.9	28.9	28.7	25.1	20.4	17.2	21.5	24.4	20.4
	±7.8	±7.3	±6.4	±7.4	±5.4	±7.6	±6.5	±5.4	±5.3	±7.3	±5.5
DBH2	24.2	27.4	27.4	32.0	30.8	27.8	21.9	19.1	23.3	27.0	23.0
	±8.0	±7.6	±6.8	±7.8	±5.7	±7.7	±6.8	±5.6	±5.5	±8.0	±5.8
HT1	20.1	22.1	25.2	27.4	26.4	22.6	20.6	18.0	21.1	22.5	20.6
	±4.6	±4.6	±3.8	±4.3	±3.7	±5.3	±4.4	±3.8	±3.4	±5.0	±3.4
CR	0.36	0.41	0.39	0.33	0.41	0.44	0.31	0.38	0.35	0.38	0.40
	±.09	±.09	±.12	±.09	±.10	±.09	±.08	±.11	±.09	±.08	±.12
BA	14.0	14.3	15.9	15.9	14.2	13.3	15.4	16.1	14.8	13.6	16.4
	±4.9	±4.4	±5.3	±4.7	±5.3	±4.2	±2.4	±4.6	±4.4	±4.3	±4.0
BAR	0.54	0.53	0.60	0.57	0.54	0.53	0.59	0.65	0.58	0.54	0.63
	±.16	±.14	±.18	±.14	±.15	±.13	±.11	±.19	±.15	±.12	±.17
ELEV	1284	982	752	939	806	1047	1055	1169	946	894	1015
	±118	±204	±105	±217	±125	±192	±139	±223	±204	±145	±204
TASP	0.35	1.27	1.15	0.96	1.11	1.18	1.45	0.72	1.24	1.46	1.10
	±.51	±.66	±.44	±.61	±.62	±.59	±.56	±.52	±.71	±.63	±.68
GRAD	42	38	21	31	33	38	41	40	29	35	30
	±17	±19	±22	±17	±13	±13	±16	±14	±15	±11	±17
TSI	0.02	0.01	0.03	0.04	0.04	0.02	-0.02	0.02	0.02	0.02	0.04
	±.05	±.04	±.04	±.06	±.07	±.03	±.05	±.04	±.05	±.05	±.06
LFI	0.25	0.20	0.25	0.25	0.27	0.21	0.16	0.23	0.18	0.21	0.19
	±.06	±.07	±.08	±.08	±.08	±.06	±.05	±.08	±.05	±.07	±.06
LAT	35.7	35.7	36.0	35.8	35.9	36.2	35.5	35.9	35.8	35.6	35.7
	±.2	±0.4	±0.5	±0.4	±0.5	±0.5	±0.2	±0.3	±0.4	±0.4	±0.4
LON	82.7	82.8	82.6	82.8	82.8	82.1	82.8	82.5	82.6	82.8	83.0
	+0.7	+0.7	+0.6	+0.8	+0.8	+0.7	+ 0.4	+0.4	+0.5	+0.5	+0.8

[a]Prse=Prunus serotina, Quru=Quercus rubra, Qual=Quercus alba, Litu=Liriodendron tulipifera, Quve=Quercus velutina, Masp= Magnolia spp, Rops= Robinia pseudoacacia, Besp= Betula spp., Qupr=Quercus prinus, Quco= Quercus coccinea, Acru= Acer rubrum

Table 4: Pearson correlation coefficients (r) of ln(DDS) with independent variables by species in the Southern Appalachian Mountains.

Independent Variable	Species[b] Prse	Quru	Qual	Litu	Quve	Masp	Rops	Besp	Qupr	Quco	Acru
Ln(DBH)	0.61	0.72	0.66	0.62	0.51	0.60	0.65	0.52	0.52	0.78	0.56
DBH^2	0.57	0.70	0.61	0.60	0.49	0.61	0.64	0.48	0.53	0.75	0.53
BAL	-0.79	-0.58	-0.76	-0.73	-0.65	-0.42	-0.47	-0.50	-0.71	-0.75	-0.58
CR	0.45	0.28	0.09	0.40	0.29	0.08	0.38	0.12	0.23	0.42	0.32
BA1	-0.20	0.06	-0.47	-0.42	-0.31	-0.03	0.03	-0.29	-0.41	-0.07	-0.20
BAR	-0.38	-0.06	-0.49	-0.43	-0.29	-0.04	-0.41	-0.43	-0.39	-0.12	-0.22
ELEV	0.04	-0.07	0.20	0.01	0.04	-0.36	0.49	-0.04	0.13	-0.26	0.20
TASP	-0.03	-0.16	0.05	0.23	0.17	0.16	-0.57	0.14	-0.06	-0.25	-0.01
GRAD	0.05	-0.18	-0.03	0.38	-0.03	-0.20	0.29	0.09	0.29	-0.12	0.11
TSI	0.01	0.12	-0.23	-0.01	-0.18	0.32	0.27	-0.16	0.10	0.03	0.04
LFI	-0.12	0.14	0.23	-0.17	-0.18	0.18	0.23	0.02	0.11	0.18	-0.08
LAT	-0.32	0.19	-0.17	-0.02	0.13	0.08	0.27	-0.24	-0.17	0.18	0.07
LON	0.24	0.06	0.16	0.00	-0.19	-0.05	0.12	0.19	0.08	0.05	-0.02

[a]Levels of significance: bold=0.01, *bold and italic*=0.001, *bold, italic and underlined*=0.0001.

[b]Prse=Prunus serotina, Quru=Quercus rubra, Qual=Quercus alba, Litu=Liriodendron tulipifera, Quve=Quercus velutina, Masp= Magnolia spp, Rops= Robinia pseudoacacia, Besp= Betula spp., Qupr=Quercus prinus, Quco= Quercus coccinea, Acru= Acer rubrum.

occurred, which were typically slightly convex. The relatively large mean values of LFI for plots with black oak, white oak, and yellow-poplar indicates field sites that were generally situated on lower slope positions. The typical field plots occupied by black locust, chestnut oak and red maple were judged to occur on middle slope positions. Coefficients of variation of site effects were lowest for ELEV and LFI, indicating relatively narrow ranges of occurrences compared to GRAD and TASP, which had a broader range of variation.

3.1 Independent variables. Correlations of ln(DDS) with ln(DBH1), DBH1^2, and BAL were highly significant for all species (Table 4). Periodic diameter growth was significantly correlated with CR for 8 of the 11 species. Significance of other measures of competition (BAR, BA1) was inconsistent among species. Generally, two or three site effects were significantly correlated with ln(DDS), but all were insignificant for two species: black cherry and black oak. The relationship of site effects with ln(DDS) was illogical for some species. For example, GRAD was significantly negatively correlated with ln(DDS) of northern red oak but positively correlated with growth of yellow-poplar, which is counterintuitive because both species are mesophytic and can occur on the same site. The relationships of both TSI and LFI with growth of yellow-poplar were negative, indicating growth of this species increases with convex plots and landforms, which is opposite of other findings (McNab 1989, 1993). Neither LAT nor LON were well correlated with ln(DDS). GEO (not shown in Table 4) was significantly correlated with ln(DDS) for only two species: black cherry (p = 0.001) and birches (p = 0.01).

Many site effects of the 62 analysis plots were significantly correlated with one another (Table 5). Site effects particularly highly correlated were ELEV with TASP and GRAD, TSI and LFI, and LAT and GRAD. The high level of correlation between TSI and LFI indicates concave plot surfaces were

Site effects	Site effects						
	ELEV	TASP	GRAD	TSI	LFI	LAT	LON
ELEV	---	-0.30	*0.42*	**-0.20**	**-0.01**	-0.33	**-0.24**
TASP	*-0.45*	---	0.04	*-0.43*	*-0.50*	**-0.01**	**-0.19**
GRAD	*0.36*	0.04	---	0.01	-0.14	*-0.61*	0.37
TSI	**-0.12**	*-0.41*	0.01	---	*0.56*	**-0.10**	0.32
LFI	**-0.13**	-0.25	-0.07	*0.44*	---	**-0.11**	0.28
LAT	-0.26	0.01	*-0.50*	**-0.14**	**-0.12**	---	*-0.84*
LON	**0.17**	**-0.21**	*0.30*	*0.39*	0.25	*-0.85*[*]	---

associated with large concave landforms (such as valleys). With the exception of TASP, the pattern of correlation was generally similar among site effects on 43 of the 62 plots on which yellow-poplar occurred. The high level of correlation among site effects indicated the likelihood of introducing multicollinearity by overfitting the yellow-poplar model with intercorrelated variables. Effects of tree size and competition were also intercorrelated: BAL with ln(DBH) ($r = 0.47$, $p = 0.0001$ to $r = 0.76$, $p = 0.0001$) and BAL with CR ($r = 0.15$, $p = 0.03$ to $r = 0.59$, $p = 0.0001$) for all species.

3.2 Formulation. BAL and a function of DBH (either ln(DBH1) or $DBH1^2$) were the two most important model components accounting for variation in ln(DDS) for most species (Table 6). For three species--black cherry, black oak and magnolia--only BAL or a function of DBH1 was significant, not both. BA1 was important for red maple. CR, LON, and GEO were not significant for any species. Yellow-poplar was the only species for which a site effect (GRAD) was the second most important independent variable. Mallows C_p varied widely from 0.37 for magnolias (with three terms in the model) to 20.4 for scarlet oak (*Q. coccinea*) (also with three terms in the model) and was not particularly useful for model formulation with this data set. Multiple coefficients of determination (R^2) averaged about 0.55 and individual values by species generally were not associated with the number of significant variables included in a model.

The influence of environmental variables on ln(DDS) was inconsistent among species (Table 6). The model formulations of only seven species were significantly affected by site effects and four of these models included only a single variable. Gradient was significant in models of four species and based on its performance in the validation tests for yellow-poplar, was considered as the most important site effect. After inclusion of three or four variables, the stepwise regression typically included additional variables (particularly site effects) not significantly correlated with ln(DDS) (Table 4), which resulted in marginal reduction of model residual sums of squares and a small (<0.02) increase of R^2. Some models were biologically illogical because signs were opposite between the correlation coefficient and the regression coefficient of the same variable.

A surprising feature of all models was the omission of CR as a significant variable. Wykoff (1990) and Stage and Wykoff (1998) found CR important for predicting diameter growth of a number of western conifers. Shifley (1987) reported CR was an important variable in individual tree basal area growth models for eastern hardwoods. In other, concurrent work to develop models of individual tree growth

Table 6: Parsimonious model formulation[a] by species in the Southern Appalachian Mountains.

Variable	Species[b,c] Prse	Quru	Qual	Litu	Quve	Masp	Rops	Besp	Qupr	Quco	Acru
ln(DBH1)	ns	*1*	*2*	ns	ns	ns	ns	*1*	ns	*1*	*1*
DBH1^2	ns	ns	ns	*3*	ns	*1*	*1*	4	*2*	ns	ns
BAL	*1*	2	*1*	*1*	*1*	ns	ns	ns	*1*	2	ns
CR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
BAR	ns	ns	*3*	ns	ns	ns	2	2	ns	ns	ns
BA1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	2
ELEV	ns	ns	ns	ns	ns	ns	ns	*3*	ns	ns	ns
TASP	ns	3	ns	ns	ns	ns	ns	ns	ns	ns	ns
GRAD	ns	ns	ns	*2*	ns	ns	ns	ns	*3*	ns	3
TSI	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	4
LFI	ns	ns	ns	4	ns	ns	ns	ns	ns	ns	ns
LAT	2	ns	ns	ns	ns	2	ns	ns	ns	ns	ns
LON	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
GEO	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C_p	6.7	4.1	14.2	6.0	1.6	-0.7	-1.3	17.5	4.2	24.1	4.4
R^2	0.74	0.58	0.65	0.62	0.43	0.44	0.55	0.57	0.59	0.73	0.51

[a]Levels of significance: bold=0.01, *bold and italic*=0.001, *bold, italic and underlined*=0.0001.
[b]Prse=Prunus serotina, Quru=Quercus rubra, Qual=Quercus alba, Litu=Liriodendron tulipifera, Quve=Quercus velutina, Masp= Magnolia spp, Rops= Robinia pseudoacacia, Besp= Betula spp., Qupr=Quercus prinus, Quco= Quercus coccinea, Acru= Acer rubrum
[c]Numbers in each species column indicate order of entry of significant variables into the model.

of hardwoods in the southern United States, CR is an important and significant variable (Personal communication D.Donnelly, USDA Forest, November 1999). In our study, the lack of significance of CR probably resulted from several factors, including the range of this variable was reduced by thinning and the measured CR reflected previous, unthinned stand conditions.

Our overall results generally agree with findings of Harrison and others (1986) who reported that basal area (and stand age) was an important variable affecting basal area growth of individual trees of most species and environmental variables generally had little significant influence on diameter growth. In contrast Wykoff (1990) reported, that topographic variables were highly significant in models ofdiameter growth for principal species of western conifers. Shifley (1987) reported that formulations of individual-tree diameter equations for 22 eastern hardwoods included components of tree size (i.e. DBH, crown ratio), competition (i.e. tree basal area), and site quality (i.e. site index). The lack of significant effect of environmental variables probably was due to: (1) reduced range of variation in ln(DDS) resulting from locating plots mainly on higher quality sites, and (2) reduced range in magnitude of environmental variables represented in the data set resulting from clustering a large number of plots at relatively few field locations. Although the analysis data set may be well suited for its intended purpose of evaluating growth and yield relations of thinned hardwood stands, weaknesses appear when it is used for other purposes, such as evaluating site factors affecting tree growth.

GEO was not a significant component of the model for any species when it was included as a categorical variable. In addition to the classification we evaluated, Hatcher (1981) suggests other potential groupings of rock types that may affect tree growth and that could be related to soil texture or fertility. Effects of geologic rock type also might have a stronger influence on species composition than growth rate of trees (Rohrer 1983). However, McNab and Merschat (1990) reported geologic variables affected height of yellow-poplar trees, suggesting that other classifications of rocks could be a significant categorical component for certain species.

The overall cumulative relationship of size, competition, and site effects in explaining variation of ln(DDS) is summarized by species in Fig. 2. Total percent variation of ln(DDS) explained ranged from 43 to 74. For most species, the first variable entering the model (usually either a size effect or BAL) explained most of the variation associated with ln(DDS), except for birch, where size and competition

were about equally important. Overall, site effects were generally unimportant in explaining variation of ln(DDS) for the oaks, but did account for practical amounts of variation for four species: black cherry, yellow-poplar, magnolia, and birch. The lack of importance of site effects conflicts with our previous study (McNab and Lloyd In prep) in which many topographic variables were superior to site index in accounting for variation of ln(DDS). The importance of environmental factors in accounting for variation of ln(DDS) may be lower due to the following reasons: topographic variables (particularly ELEV and GRAD) were strongly correlated with BAL, which accounted for much of the variation in ln(DDS) because it entered the model first and restrictions for entry of variables into the model were more stringent in this study.

Compared with similar models developed by Harrison and others (1986), our models generally explained a smaller proportion of variation (R^2) in growth for most species (Table 1, Fig. 2). Our models explained more variation only for white oak, birch, chestnut oak, and red maple. The principal difference between models of the two studies was inclusion of age as an independent variable of most species by Harrison and others (1986). However, they found age was not significant for several species including birch and red maple (Table 1), which were two of the species that our models explained a larger proportion of variation in growth. Performance of our yellow-poplar model in explaining variation in diameter growth was about midway between the best and poorest of all species in our comparison, but explained about 5 percent less variation in diameter growth compared with the formulation by Harrison and others (1986).

3.4 Yellow-Poplar Model validation and bias. Yellow-poplar occurred on 43 of the 62 analysis plots and intercorrelations of the site effects far5iables and ln(DDS) were similar to the total data set (Table 5), except that ELEV and TASP were correlated at a lower level of significance (p = 0.05). The yellow-poplar model was typical of other species in terms of formulation and evaluation statistics; we examined it in detail and tested it for accuracy using an independent data set. The model formulation consisted of four variables (Table 6) that explained about 62 percent of variation in ln(DDS). All variables were highly significant (p<0.001) except LFI, which entered the model last. Most variation was explained by BAL ($R^2 = 0.54$), the first variable to enter the model. Additional variation explained by each successive variable entering the model was: GRAD ($R^2 = 0.02$), DBH^2 ($R^2 = 0.04$), and LFI ($R^2 = 0.02$). Evaluation criteria that included four significant independent variables, stringently fitting the model for site effects, relatively high R^2 of model formulations, and acceptable levels of C_p suggested the derived model satisfactorily expressed the relationship of ln(DDS) for yellow-poplar and therefore should perform well with the validation data set.

Residuals (actual - predicted) of the model developed with 146 trees of the analysis data were not correlated with tree DBH (r=0.015, p=0.83), plot site index (r = 0.007, p = 0.93), or stand age (r = -0.043, p = 0.61). In relation to DBH, residuals were homogeneously distributed (within a band of +1ln(DDS) except for one tree (indicated by arrow) that grew only about 0.5cm in DBH during the five year measurement interval (Fig. 3). This tree was initially considered an outlier resulting from error in

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Percent variation explained

Black cherry 74
N. red oak 58
White oak 65
Yellow-poplar 62
Black oak 43
Magnolia 44
Black locust 55
Birch 57
Chestnut oak 59
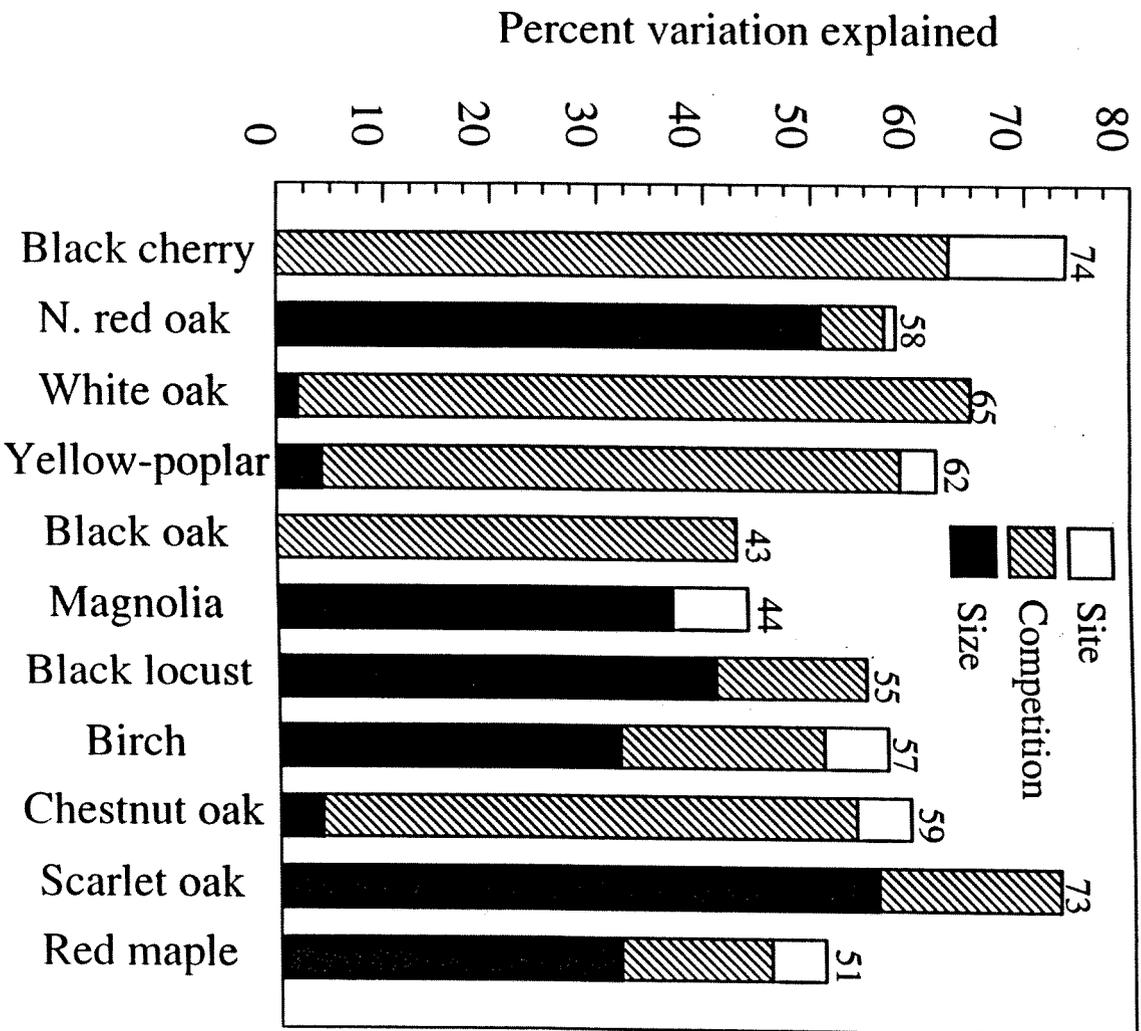Scarlet oak 73
Red maple 51

Legend: Site, Competition, Size

Figure 2: Proportion of total variation of individual tree diameter growth explained by three types of variation associated with tree size, competition, and site effects by species.
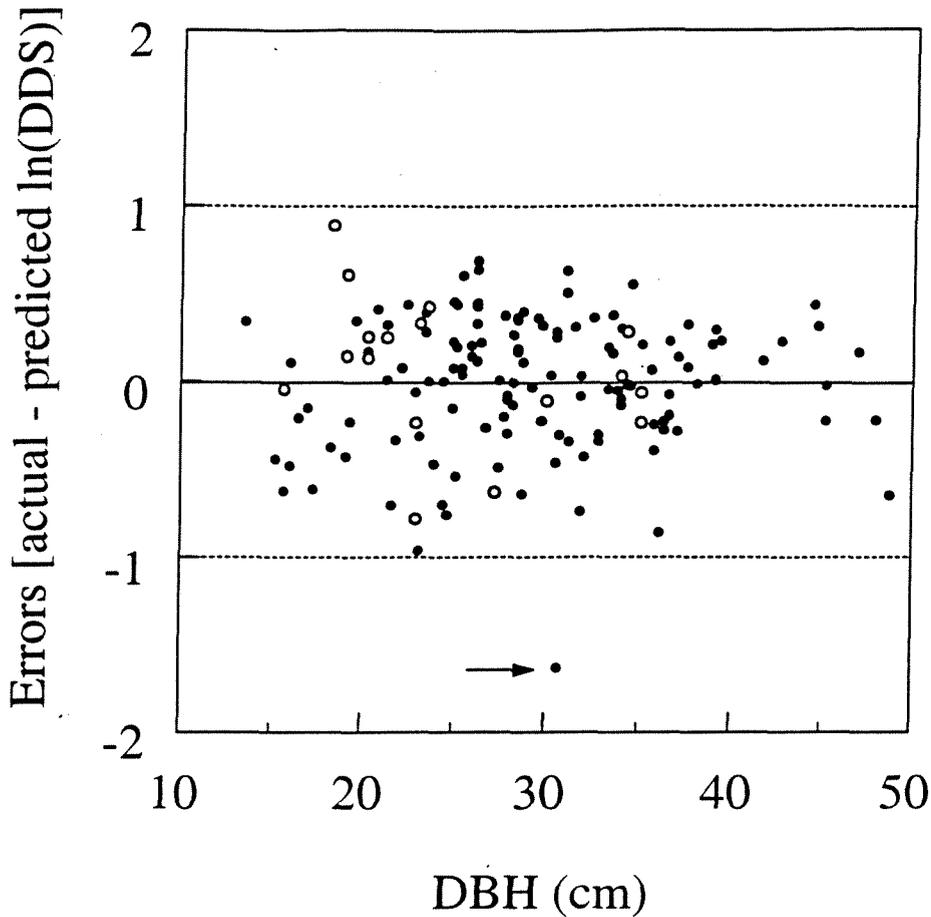
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Figure 3: Residuals of the "best" diameter growth model for yellow-poplar in multispecies stands in relation to DBH for all trees (●○) used in model development. Trees with particularly large residuals occurring on a single plot (○) are discussed in the text. The tree identified by an arrow (→) is explained in the text.

DBH measurement, but was retained in the analysis data set because examination of subsequent periods of growth indicated a consistent trend. Detailed examination of errors associated with the single plot in which the tree with largest positive residual occurred revealed 16 other yellow-poplars, some of which had among the largest negative residuals of the entire data set. All trees were dominant or codominant crown classes and most had about the same DBH (20-35 cm). However, because these 17 trees were all responding in growth to about the same magnitude of site effects but exhibited widely differing ln(DDS), we suggest that other unmeasured factors not associated with tree size, competition, and site effects was contributing to the large residuals. These factors may be associated with previous site disturbances, competition before thinning, or tree physiological and genetic differences. In results from a similar attempt to predict growth of individual eastern hardwoods in which about half of the variation was unexplained, Shifley (1987) stated: "The effects of weather, microclimate, macroclimate, irregular spacing, soils, pollutants, genetics, and other factors are unaccounted for in the current model and are undoubtedly responsible for a significant portion of unexplained variation in tree growth." Evaluation criteria of highly significant variables, restricted site effects variables, relatively high R^2, and one of the most favorable values of C_p achieved among all species suggested the derived model satisfactorily represented the relationship of ln(DDS) for yellow-poplar based on the analysis data set and would perform well with the validation data set.
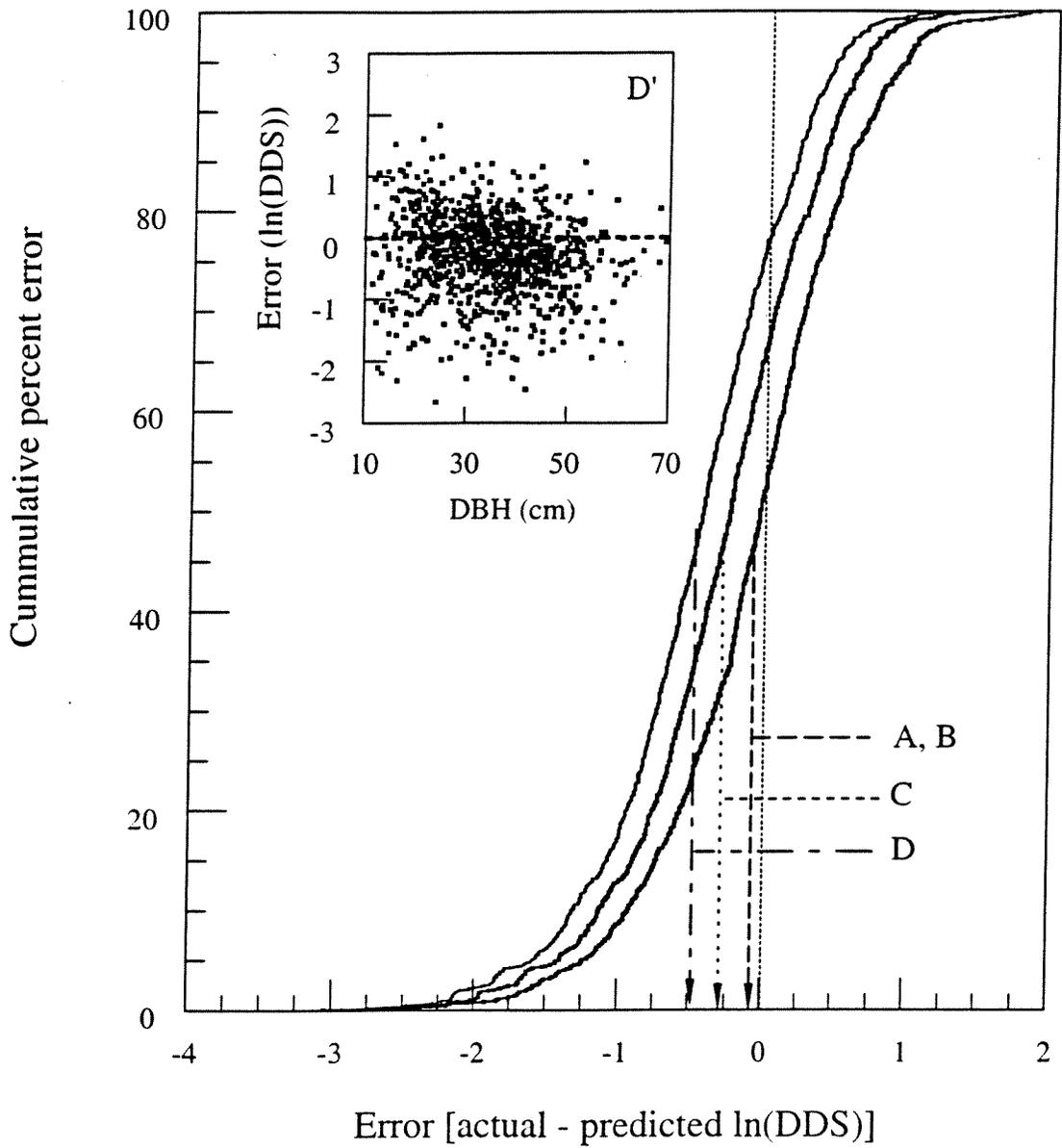
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Figure 4: Cumulative percent error of four progressively complex yellow-poplar individual tree diameter growth models (Table 7) applied to an independent validation data set. Arrows pointing to the x-axis indicate bias of each model. Inset (D') shows errors of model D in relation to DBH.

Table 7: Accuracy of progressively fitted formulations of yellow-poplar ln(DDS) tested with an independent data set.

Formulation	MSE	Bias[a]	Confidence Interval	Prediction Interval	Tolerance interval[b] (cm^2)	(%)
A: BAL	0.439	-0.074	±0.042	±1.29	±1.46	39.1
B: BAL+GRAD	0.426	-0.074	±0.041	±1.27	±1.44	39.2
C: BAL+GRAD+DBH1^2	0.485	-0.287	±0.040	±1.25	±1.41	39.5
D: BAL+GRAD+DBH1^2+LFI	0.620	-0.468	±0.040	±1.24	±1.41	41.0

[a]Bias = Average of (Actual growth - Predicted growth).
[b]Precision = Tolerance interval = 95% probability that 95% of the long-term prediction errors will fall in this interval.

However, subsequent testing (results not presented here) of reduced model formulations indicated the effect of size was probably the primary source of bias in the earlier study. These results suggest that the yellow-poplar analysis model may not be sufficiently accurate for application in pure stands without inclusion of other independent variables, or that use of data from a pure stand is not appropriate to test the present model, which was developed in a mixed stand. We suggest, however, that operational models must be adequately robust if they are used in stands with a wide range of species composition.

We tested the relationship of tree height as a function of DBH in the analysis and validation data sets and found the two models were significantly different (p<0.01). In pure stands, large (DBH> 50cm) yellow-poplar trees were significantly taller (by 2.2 m) and small trees (DBH<20 cm) were shorter (by 2.0 m) than yellow-poplar trees of similar DBH growing in mixed-species stands. We did not examine the likely effect of the different height-diameter relationships on model performance. Variation in mean site quality between the two data sets not explained by site variables included in the models could account for the difference (Fulton 1999). Huang and Titus (1994) developed age-independent height-DBH models of individual white spruce (*Picea glauca*) and trembling aspen (*Populus tremuloides*) in mixed stands and found a number of significant variables, including basal area and site quality. Liu and Burkhart (1994) report that shade-intolerant loblolly pines (*Pinus taeda*) in pure stands were taller than similar pines in mixed hardwood stands and suggest these differences are related more with site conditions than with inherent differences in growth response of species in stands of varying composition. Height growth models have been developed also for mixed stands and may be equally complex as diameter in affecting DBH growth.

4   CONCLUSIONS

We demonstrated in this study that the general age-independent formulation used for western conifers (Wykoff 1990) is appropriate to model individual tree diameter growth of 11 major hardwood species in the Southern Appalachian Mountains. More specifically, we found in our assessment that five-year periodic diameter increment of all species was highly correlated with variables associated with tree size and competition but was less correlated with site-effect variables. Parsimonious models consisting of several size and competition variables accounted for 43 to 74 % of the variation in five-year periodic growth among all species, but did not include crown ratio. Environmental (site) effects accounted for small but significant amounts of variation in increment for over half of the species, but no single site variable was consistently important for a majority of species. Validation of the best yellow-poplar model with a large independent data set suggested an appropriate formulation, but revealed a source of bias that could not be explained. We suggest that yellow-poplar responds differently to mutual competition originating from different species compared to other yellow-poplar trees and we suggest also that a more complex model (probably involving height relationships) will be required to achieve greater accuracy in estimates of diameter growth. Validation of growth models with independent data sets, or by other means, is essential to ensure that relationships developed with sample data sets from small geographic areas will be applicable in other, much larger samples of the population. Further evaluation of our model formulations with data from other locations across a broad portion of the

Southern Appalachian Mountains is advised.

The surprising lack of significance of a measured competition variable and the unexplained source of bias found in our study suggests several hypotheses for further investigation:

1. The effect of crown ratio on diameter growth of individual trees is significant in unthinned stands.

2. The effect of tree size on diameter increment is not consistent among individual yellow-poplars in mixed-species stands compared to yellow-poplars in almost pure stands.

3. The height growth relationship of individual yellow-poplar trees in mixed-species stands varies from that of individual yellow-poplar trees in almost pure stands and in addition to age is influenced by site quality and stand density.

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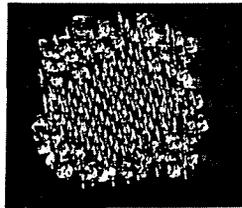
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