Chapter V

A Stand Basal Area Growth Disaggregation Model Based on Dominance/Suppression Competitive Relationships

Introduction

Forest growth and yield models were traditionally classified into one of three broad categories based on model resolution (Munro 1974): whole-stand, individual-tree distance independent, individual-tree distance dependent. Within the frame work of whole-stand models, various size-distribution models are used to partition stand-level growth estimates into idealized diameter or product classes. One of the most common methods is to assume an idealized probability density function. Since the early 1900's, a variety of mathematical distributions have been utilized to develop stand tables (Cajanus 1914, Meyer 1930, Schnur 1934, Bliss and Reinker 1964, Nelson 1964, Clutter and Bennett 1965, Bailey and Dell 1973).

Initially, parameters of the specified distribution were predicted from stand-level attributes such as basal area, number of trees, or site index. These parameter prediction equations seldom accounted for much of the observed variation across stand conditions. Later efforts have focused on parameter recovery techniques. In this approach, attributes of a dbh distribution are used to solve for analytical equivalents in the probability density function.

Diameter distribution models are often used for inventory projections of tree-list data. With both the parameter prediction and parameter recovery techniques it can be argued that neither method completely utilizes such data. Borders *et al.* (1987) developed a diameter distribution model based on percentiles across an observed diameter distribution. This approach does not assume an idealized distribution and can reproduce uni-modal, and multi-modal distributions.

In situations where an initial tree list is available, methods have been developed to disaggregate stand-level growth projections from whole-stand models over the initial dbh distribution. These approaches represent an attempt to combine whole-stand and individual-tree distance independent models (Ritchie and Hann 1997a). Recently, several approaches have been developed to disaggregate stand-level growth over initial tree-lists (Harrison and Daniels 1988, Pienaar and Harrison 1988, Zhang *et al.* 1993, Ritchie and Hann 1997b). Since estimates of future size distributions are conditioned on stand-level estimates, these models tend to provide reliable estimates of long-term growth while providing individual-tree resolution and utilizing initial tree lists when available.

Borders and Patterson (1990) compared a traditional diameter distribution model, a percentile-based projection model, and a basal area disaggregation model in projecting even-aged loblolly pine plantations. The disaggregation model (Pienaar and Harrison 1988) performed best. Ritchie and Hann (1997b) evaluated several disaggregation and individual-tree models over a 5-year growth interval with Douglas-fir. In general, the individual-tree models were superior for estimating stand and tree growth.

The objective of this study was to explore further the utility of disaggregation models for projecting observed tree lists. In particular, the resource pre-emptive nature of intra-specific competition and the resultant relationship between dbh relative growth rate and relative size (see Chapter IV) can be used as a basis for a basal area growth disaggregation model.

Data and Methods

Let *d* denote an individual tree's dbh and *t* denote time. The instantaneous relative growth rate (r) of dbh is defined as (Fisher 1921)

$$r = \frac{1}{d}\frac{\partial d}{\partial t} \qquad [5.1]$$

Whatever the distribution of r, the mean relative growth rate ($\bar{r}$) over any time interval is given by

$$\bar{r} = \frac{\ln(d_2) - \ln(d_1)}{(t_2 - t_1)} \qquad [5.2]$$

where the subscripts reference time 1 and 2. The diameter at time 2 is given by

$$d_2 = d_1 e^{\bar{r}(t_2 - t_1)} \qquad [5.3]$$

Assuming a linear relationship between relative growth rate and relative size (see Chapter 4), relative growth rate for the i'th tree is

$$\bar{r}_i = \alpha_0 + \alpha \frac{d_i}{d_m} \qquad [5.4]$$

where d_m is the median diameter. So,

$$d_{2i} = d_{1i} e^{\left(\alpha_0 + \alpha \frac{d_{1i}}{d_{1m}} \right) (t_2 - t_1)} \qquad [5.5]$$

From equation [5.5], basal area at time 2 (B_2) is given by

$$B_2 \ = \ k \sum_{i=1}^{n} \left(d_{i1} e^{\left(\alpha_0 + \alpha \frac{d_{i1}}{D_m} \right) (t_2 - t_1)} \right)^2 \qquad [5.6]$$

where k = 0.005454 (when dbh is in inches and basal area in sq.ft/acre).

Given an estimate for α, equation [5.6] can be solved for α_0 such that equation [5.4] can be used to disaggregate stand basal area growth over the initial tree list. Solving equation [5.6] for α_0 yields

$$\alpha_0 \ = \ \frac{1}{2(t_2 - t_1)} \ln \left(\frac{B_2}{k \sum_{i=1}^{n} \left(d_{i1} e^{\alpha \frac{d_{i1}}{D_m} (t_2 - t_1)} \right)^2} \right) \qquad [5.7]$$

Tree-list projections from the above approach were compared with two other disaggregation models reported in the literature. Citing Hilt's (1983) contention that basal area growth is proportional to initial basal area and Ziede's (1986) argument that diameter increment is linearly related to initial diameter, Harrison and Daniels (1988) assume basal area increment is linearly related to initial basal area:

$$\Delta b = \beta_0 + \beta b \qquad [5.8]$$

Centering equation [5.8] on the intercept and rearranging yields the one parameter disaggregation function for basal area

$$\Delta b = \beta (b - \bar{b}) + \overline{\Delta b} \qquad [5.9]$$

The coefficient, β, in equation [5.9] was modeled as

$$\beta = \beta_1 e^{\beta_2 S} H_D^{\beta_3} \qquad [5.10]$$

Following Clutter and Jones (1980), Pienaar and Harrison (1988), and Pienaar (1989) developed a disaggregation model from the assumption that relative size over time, in terms of individual tree basal area to mean tree basal area, can be modeled as

$$\frac{b_{2i}}{\bar{b}_2} = \left(\frac{b_{1i}}{\bar{b}_1} \right)^{(\frac{A_2}{A_1})^{\theta}} \qquad [5.11]$$

Given an estimate of the stand basal area at time 2, the one parameter disaggregation function for basal area is given by

$$b_{2i} = B_2 \left(\frac{\left(\frac{b_{1i}}{\bar{b}_1} \right)^{(A_2/A_1)^{\theta}}}{\sum_{i=1}^{n} \left(\frac{b_{1i}}{\bar{b}_1} \right)^{(A_2/A_1)^{\theta}}} \right) \qquad [5.12]$$

The three disaggregation functions, equations [5.5, 5.9, and 5.12], were validated with the 136 locations of the Coop thinning study not used in estimating the coefficients for each model. For each plot, the initial diameter list was projected to each remeasurement age. To isolate the performance of the disaggregation functions, observed stand attributes and individual-tree mortality were used for each projection.

Model performance was based on analysis of individual tree diameter predictions, diameter distribution attributes, and product estimates. In addition, an error index (Reynolds *et al.* 1984) was computed to compare projected diameter distributions. The index was computed as a weighted sum of the absolute differences in observed and predicted number of trees in 1-inch diameter classes. Total volume per tree was the weighting factor for each class.

Model Development

Modeling Dominance/Suppression

Based on the analysis presented in Chapter 4, a model of the linear relationship between relative growth rate and relative size should exhibit the following properties:

- The slope should switch from negative to positive as the stand develops.
- The temporal trend is curvilinear.
- On a given site, the higher the initial density the sooner the transition from negative to positive slope.
- Thinning reduces the magnitude of the slope.

The annual remeasurements of the Coop spacing study provide an excellent description of the dominance/suppression relationship through time. Given the 3- to 5-year measurement intervals of the remaining studies, initial modeling was restricted to the Coop spacing study. Locations 1, 2, and 3 were used for model fitting. Location 4 was used as an independent validation dataset.

Initial model development was based largely on stepwise regression procedures relating various stand attributes and transformations of those attributes to the observed slope via the following linear model:

$$\alpha_i = \lambda_0 + \lambda_1 x_{1i} + \lambda_2 x_{2i} + \cdots + \lambda_k x_{ki} \qquad [5.13]$$

where α_i denotes the slope of the linear relationship between relative growth rate and relative size and the x_i's represent stand level attributes for the i'th plot.

During model development, equation [5.13] was fitted to the complete fitting dataset and by logical subsets (initial density, study location) of the data. When fitted by initial density across the study sites, the simple linear model with the reciprocal of site height cubed explained 42 to 81 percent of the variation in the observed slope coefficient.

Analysis of residuals indicated a violation of the assumption of homogenous variance. Figure 5.1 shows the variance in the slope coefficient varies non-linearly with stand age. Weighting the data points by the inverse of age-squared improved the distribution of residuals substantially.

To account for the effect of initial density on the temporal trend of the slope coefficient, various measures of density were incorporated into the model. In terms of the increase in percent variation explained, including the ratio of basal area to site height provided the best or nearly best model for the combined dataset and for each study location. Together, these two terms explained 74 to 86 percent of the variation in the observed slope coefficient at each study location. Including additional model terms resulted in little improvement at each location. Furthermore, no variable was consistently the best term to add to the model.

Fitting equation [5.13] to all three locations with the reciprocal of site height cubed and the ratio of basal area to site height as independent variables resulted in R^2 = 0.75 and a mean square error of 0.0973. Analysis of studentized residuals indicated the model under predicted on location 1 and over predicted location 2. Since these two sites represent the extremes in site index for the data (see Table 3.3), various transformations of a site index variable where included in the model. Including the site index term removed much of the bias at locations 1 and 2 and improved the R-square to 0.82 with a mse = 0.07364. Graphical analysis of studentized residuals (Figure 5.2) showed some extreme values but no consistent bias across age, spacing, or study location.

Analysis of studentized residuals and high leverage points (HAT diagonals) suggested one data point in particular was influencing the fit of the model. The slope coefficient and observed stand attributes for the age 5-year data for the 6 x 6 spacing at location 2, block 2 resulted in a studentized residual of 5.1 and a Hat diagonal of 0.13 (for this model a value exceeding 0.02 can potentially exert strong influence on the results (Meyers 1986)). Examination of the trend between relative growth rate and relative size for this observation (see Figure A.5) suggests the slope coefficient is providing a good description of the linear relationship for this data. Dropping the suspect data point did not change the selected dependent variables or increase the R^2 appreciably but did lower the mean square error by 7%. However, the dependent variables selected in the model building process and the magnitude of the fitted coefficients were not changed by dropping the suspect data point. Subsequently, this data point was included in the final fitted model.

The predicted slope coefficient based on observed stand parameters for the fitting data and validation data (location 4) is shown in Figure 5.3. Comparison to the observed values (see Figure 4.3) indicates the model describes the general trends and displays the main results reported above. However, there are several clear short comings. On the closest spacings, the model does not display the degree of curvature observed. At location 4, the model tends to underestimate the observed slopes for most ages but does well on the 12 x 12 spacing. Attempts to improve on these areas were unsuccessful.

The final model was refit to all four locations of the Coop spacing study. The resultant parameter estimates are shown in table 5.1 for equation [5.14]. Inspection of the variance inflation factors suggest multicollinearity between the regressors is not a problem with the final model.

$$\alpha = \lambda_0 + \lambda_1\left(\frac{1}{H^3}\right) + \lambda_2\left(\frac{B}{H}\right) + \lambda_3\left(\frac{1}{S^2}\right) \qquad [5.14]$$

Table 5.1. Parameter estimates for equation [5.9] relating the slope of the linear relationship between relative growth rate and relative size to stand parameters for the Coop spacing study. Parameter estimates based on ordinary least squares weighted inversely proportional to age-squared.

Parameter	Estimate	Std. Error	p-value	VIF
λ_0	0.101152	0.014149	< 0.01	0.000000
λ_1	-470.498258	14.992890	< 0.01	1.077228
λ_2	0.022584	0.001147	< 0.01	1.089718
λ_3	-600.913343	58.299420	< 0.01	1.079165

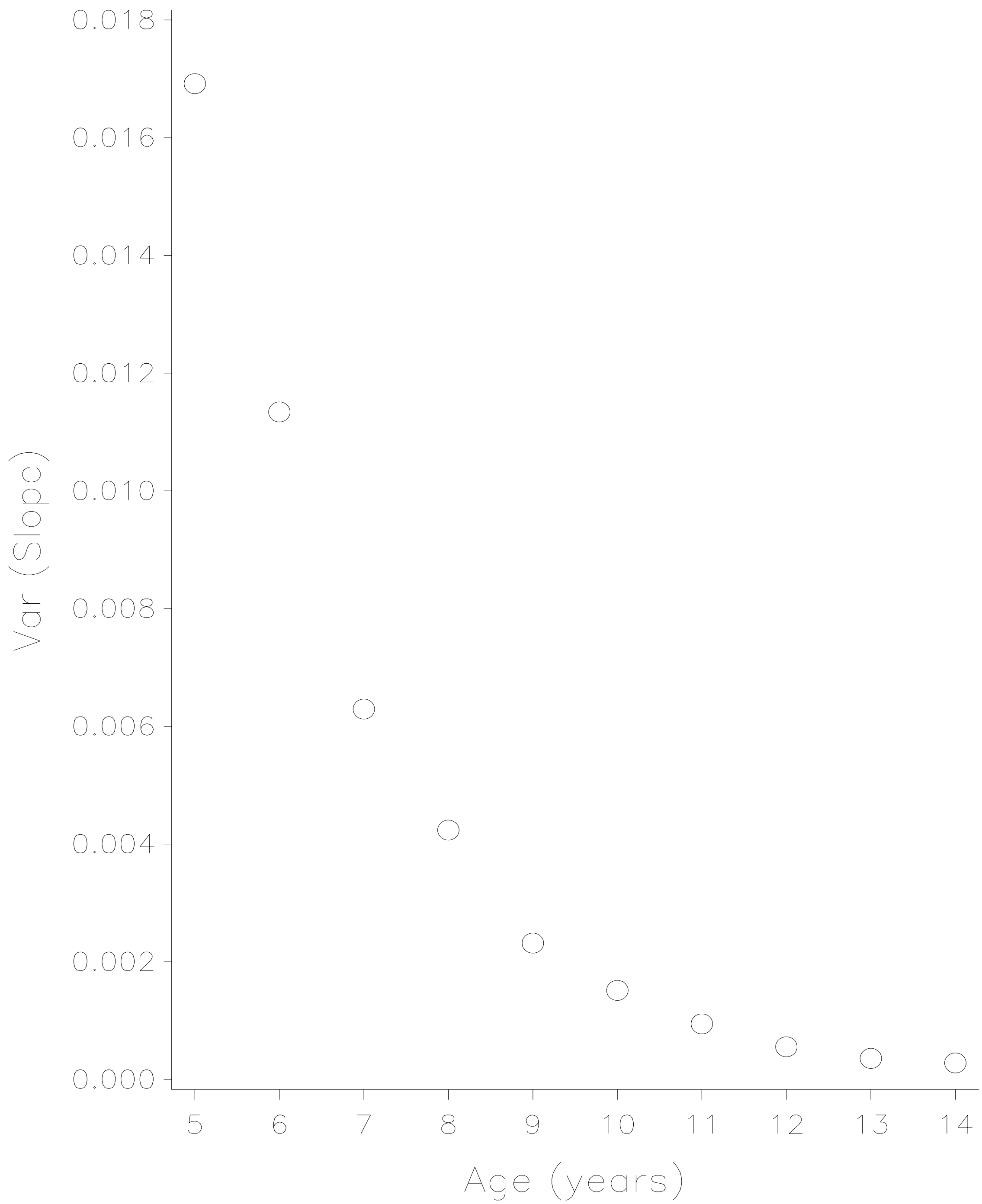

Figure 5.1. Variance in the slope of the linear relationship between relative growth rate and relative size for locations 1, 2, and 3 of the Coop spacing study. The estimated variance is based on a sample size of 36 at ages 5 to 11 and a sample size of 35 at ages 12 to 14.

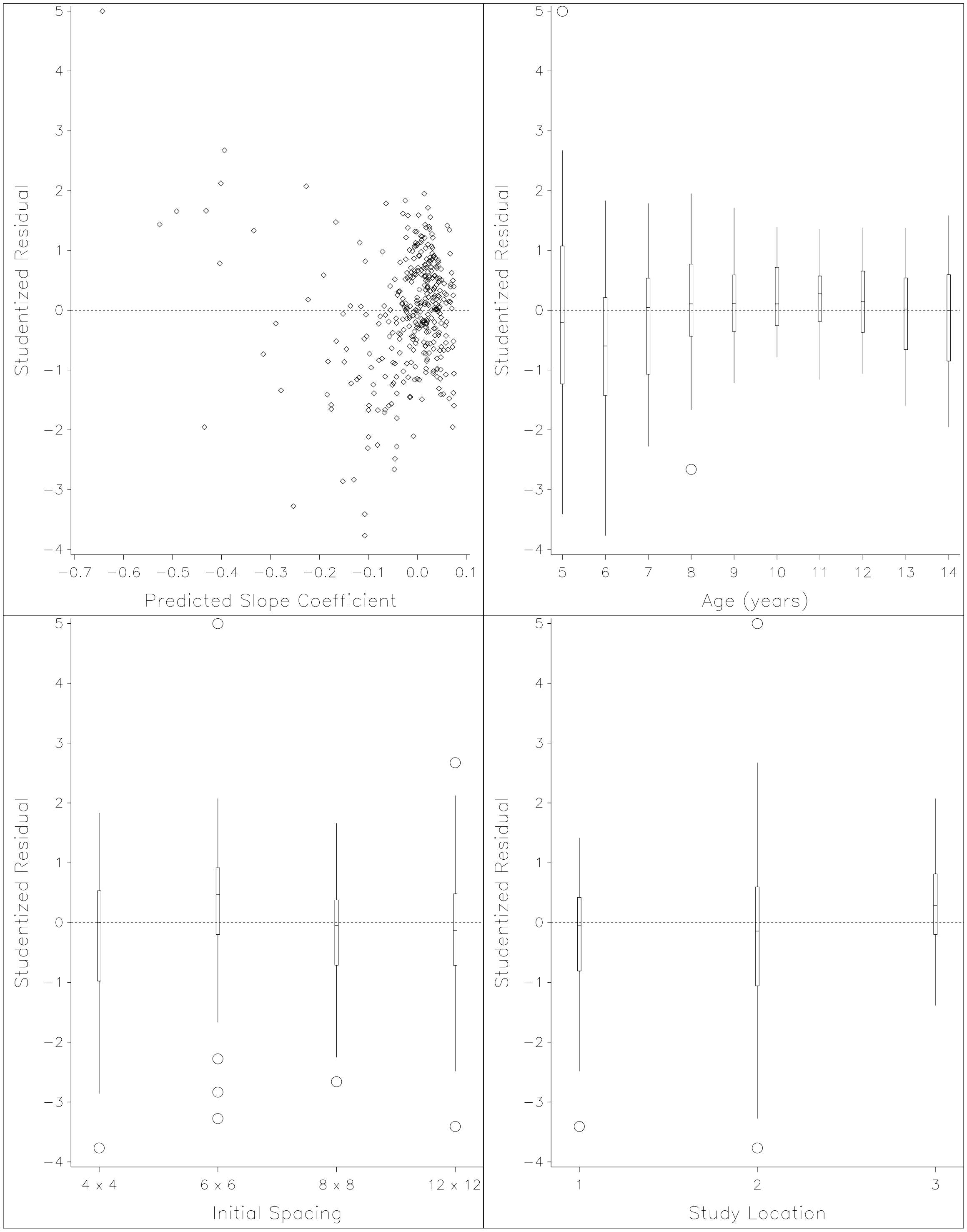

Figure 5.2. Analysis of studentized residuals from modeling the slope coefficient with the Coop spacing study locations 1, 2, and 3.

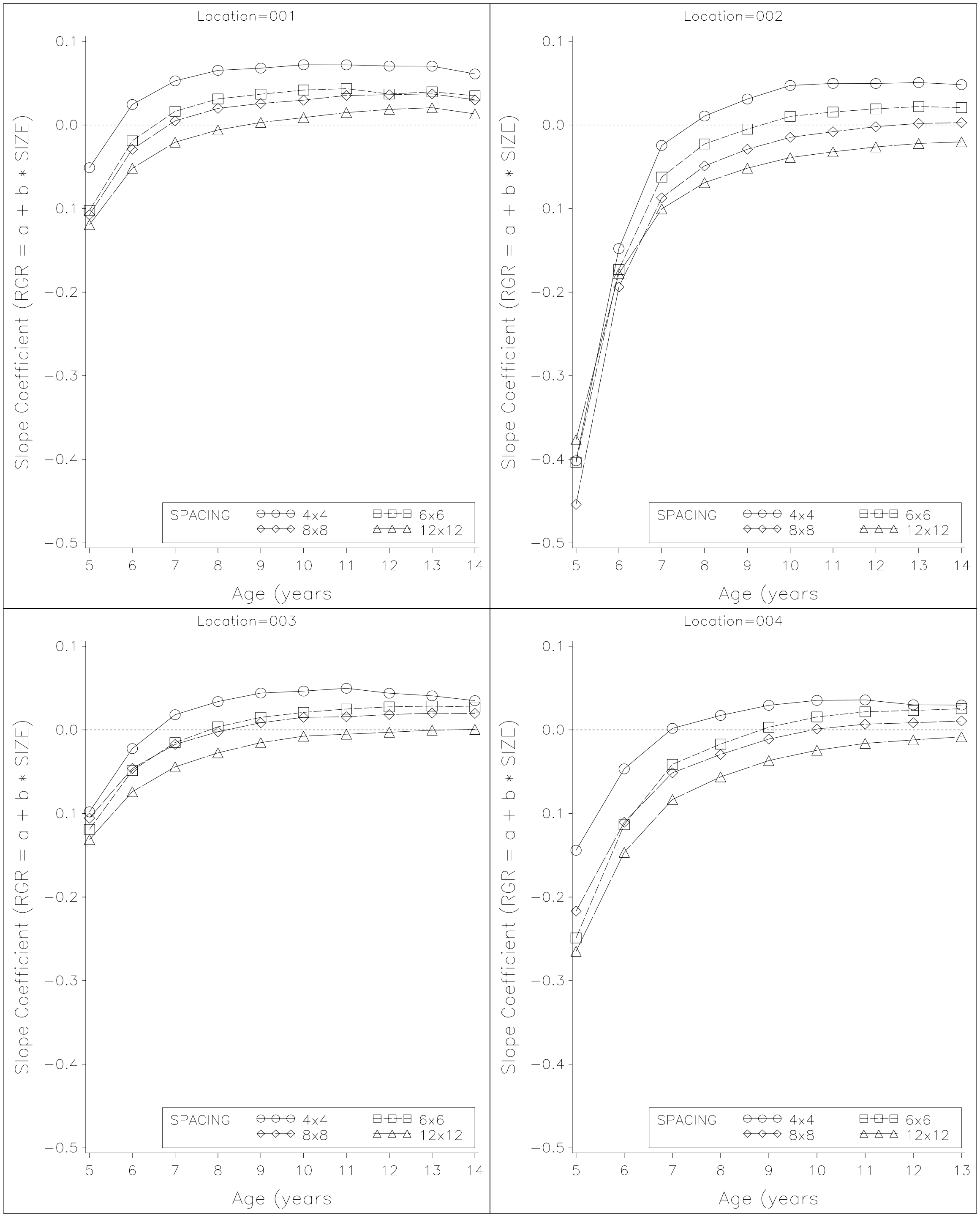

Figure 5.3. Estimated slope of the linear relationship between relative growth rate and relative size over time for the Coop spacing study. Model was fit to data from locations 1, 2, and 3.

The slope coefficient model developed from the Coop spacing study was used as the base model for modeling dominance/suppression relationships in older stands. With respect to modeling dominance/suppression trends, the quality of the data varies greatly across the studies. Simply splitting the large thinning study into nearly equal fitting and validation datasets would likely result in coefficient estimates heavily weighted toward the thinning data.

Individual locations of the thinning study were grouped into age and site index groups (Table 5.2) based on the conditions of the unthinned plot at study establishment. Three locations were randomly chosen from each age-site index group. The unthinned and thinned plots from each selected location were combined with the two spacing studies to comprise the fitting dataset. During model development, multiple random samples were drawn and the stability of coefficient estimates observed. The remaining locations of the thinning study were set aside for model validation.

Table 5.2. Age and site index classes used to select a fitting dataset via stratified random sampling.

	Site Index Class (height at age 25-years)		
Age Class (years)	< 55	55 to 65	> 65
10	6	115	4
15	17	41	16
20	14	31	18
25	6	10	6

Equation [5.14] was fitted to the Coop spacing study, Calhoun spacing study, and the unthinned plots of the selected locations from the Coop thinning study. The coefficient estimates for the height and basal area terms were very stable over the different random selections of the thinning study locations. The site index term was seldom statistically significant and changed in both magnitude and sign with each fitting dataset. Consequently, the site index term was dropped from the model. No other stand attributes were found to improve the following model

$$\alpha = \lambda_0 + \lambda_1 \left(\frac{1}{H^3} \right) + \lambda_2 \left(\frac{B}{H} \right) \qquad [5.15]$$

Analysis of residuals from the validation portion of the Coop thinning study showed no obvious relationship between errors and thinning level (Figure 5.4) over the different random selections used for model fitting. The reduction in density following thinning and subsequent effects on the slope coefficient are largely accounted for by the basal area term in the model. Consequently, the unthinned and thinned plots were combined. Following the usual procedure in cross validation, the final coefficient estimates were based on the complete dataset (Meyers 1986). Parameter estimates for equation [5.15] are given in table 5.3. The final model explained 64 percent of the variation in the slope coefficient with a mean squared error of 0.10037. Studentized residuals over predicted slope coefficients for unthinned and thinned plots of the Coop thinning are shown in figure 5.5 for each remeasurement period.

Table 5.3. Parameter estimates for equation [5.15] relating the slope of the linear relationship between relative growth rate and relative size to stand parameters for the Coop spacing, Calhoun spacing, and Coop thinning study. Parameter estimates based on ordinary least squares weighted inversely proportional to age-squared.

Parameter	Estimate	Std. Error	p-value	VIF
λ_0	-0.006061	0.00157967	< 0.01	0.000000
λ_1	-566.511754	13.63342376	< 0.01	1.01984377
λ_2	0.03255	0.00064549	< 0.01	1.01984377

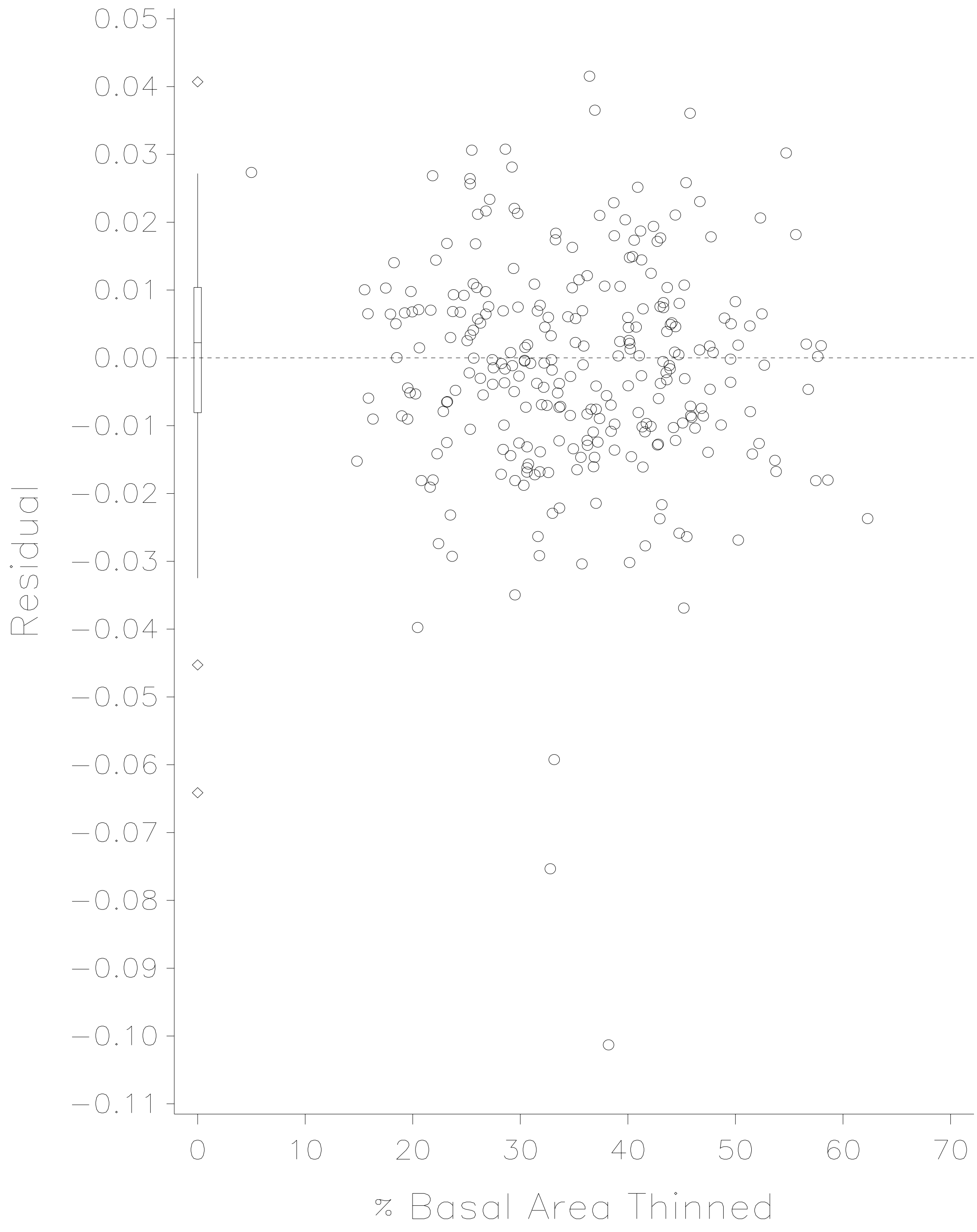

Figure 5.4. Error in slope predictions for validation portion of Coop thinning study. Pattern was similar for all random samples comprising a fitting dataset. Residuals for unthinned plots shown as a box and whisker plot.

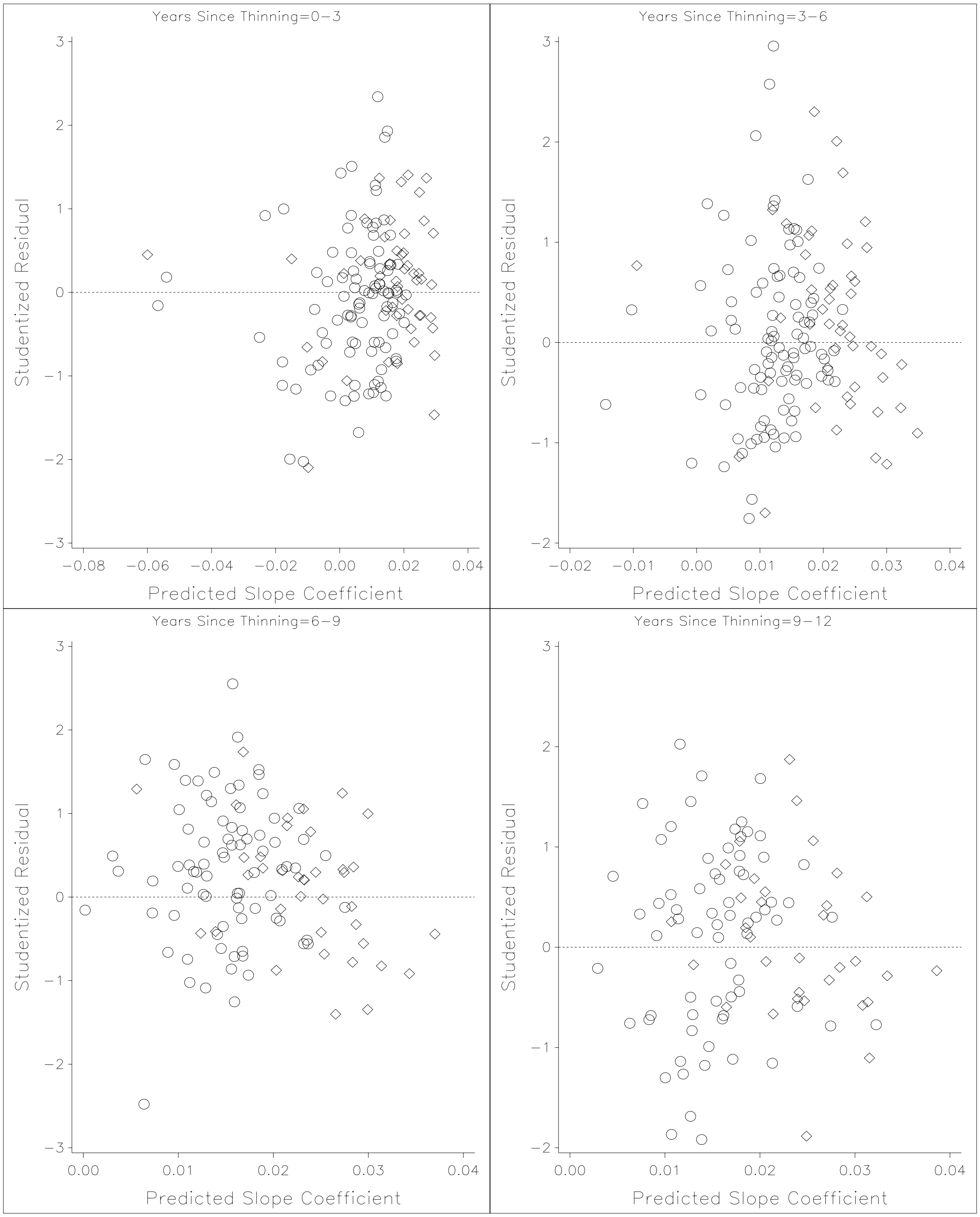

Figure 5.5. Studentized residuals and predicted slope coefficients for each measurement interval of the Coop thinning study. Diamonds denote unthinned plots, circles denote thinned plots.

Modeling Basal Area Increment

The same plots used to fit the final dominance/suppression model were used to estimate the coefficients in equation [5.8] via a resistant line (Hoaglin *et al* 1983). Analysis of the relationship between the slope coefficient of the basal area increment model and stand attributes found no substantive improvement over equation [5.10]. Subsequently, non-linear least squares were used to estimate the parameters of equation [5.10] (Table 5.4). The resultant model explained 80 percent of the variation in the slope coefficient and had a mean square error of 0.22858. The model performed equally well across unthinned and thinned stands.

Table 5.4. Parameter estimates for equation [5.10] relating the slope of the linear relationship between basal area increment and initial basal area to stand parameters for the Coop spacing study, Calhoun spacing study, and the fitting portion of the Coop thinning study.

Parameter	Estimate	Approximate Std. Error	Approximate p-value
β_1	5.435220	0.49701	< 0.01
β_2	0.022008	0.0012372	< 0.01
β_3	-1.474802	0.01723	< 0.01

Modeling Relative Size

Equation [5.11] was fit to the same plots used to fit the final dominance/suppression model and the Harrison and Daniels (1988) model. In two previous applications of this model (Pienaar and Harrison 1988, Borders and Patterson 1990) there was no reported relationship between the coefficient and stand attributes.

However, with the data used in this study, the coefficient was clearly related to site height and density. Equation [5.16] explained 53 percent of the variation and had a mean square error of 14.58829 with the coefficient estimates shown in table 5.5. The model performed equally well across thinned and unthinned stands.

$$\theta = \theta_0 + \theta_1(RS) + \theta_2\left(\frac{1}{H}\right) \qquad [5.16]$$

Table 5.5. Parameter estimates for equation [5.16] for the Coop spacing study, Calhoun spacing study, and the fitting portion of the Coop thinning study. Parameter estimates based on ordinary least squares weighted inversely proportional to age-squared.

Parameter	Estimate	Std. Error	p-value	VIF
θ_0	0.974093	0.02285181	< 0.01	0.00000000
θ_1	-2.521021	0.12431262	< 0.01	1.76299978
θ_2	-7.92368	1.12102665	< 0.01	1.76299978

Analysis and Results

The average stand attributes over the projection interval were used with equations [5.10], [5.15], and [5.16]. In subsequent discussion, the disaggregation model developed in this study is referred to as the D/S model. The Harrison and Daniels (1988) model will be referred to as the BA Increment model, and the Pienaar Harrison (1988) model will be denoted the BA Size model. Analysis of residuals is based on 12-year projections.

The ability of the three disaggregation models to project individual-tree diameter was examined by broad size classes. For each plot, diameters at plot establishment were assigned to three groups; lower quartile, upper quartile, inter-quartile. Analysis of mean residuals for individual-tree projections by dbh size classes (Table 5.6) indicates the D/S and BA Increment model under estimate growth on smaller trees and over estimate growth on the larger trees. In terms of minimizing bias, the BA Increment and BA Size models perform better than the D/S model. Within each approach, performance is similar across unthinned and thinned stands.

The mean absolute residual (Table 5.7) was computed as a measure of overall accuracy. Within each size class and across all trees, a distribution-free multiple comparison test (Miller 1966) based on Kruskal-Wallis rank sums was used to compare the models. There is little difference among the three disaggregation models in terms of accuracy.

Analysis of the projected minimum, average, and maximum dbh (Table 5.8) shows the D/S model over estimates the maximum tree size, particularly on unthinned stands. Minimum tree dbh is under estimated on unthinned stands and over estimated on thinned stands with the D/S model. The BA increment model performs well on unthinned stands, though it does under estimate minimum dbh. However, this model performs worse on thinned stands. The BA Size model performs similarly on unthinned and thinned stands. The model over estimates the minimum and average dbh.

Table 5.6. Mean residual in individual-tree dbh 12-year projections by dbh size classes.

dbh size class	n	D/S	BA Increment	BA Size
		Disaggregation Model		
		------------ unthinned -----------		
All	4,113	0.04**	-0.01	-0.02
Lower quartile	658	0.27**	0.21**	0.05*
Inter-quartile	2,116	0.15**	-0.01	-0.01*
Upper quartile	1,339	-0.26**	-0.10**	-0.06**
		------------ thinned -----------		
All	11,468	-0.00	-0.02**	-0.02*
Lower quartile	798	0.22**	0.09**	-0.03**
Inter-quartile	5,823	0.10**	0.00	-0.01
Upper quartile	4,847	-0.16**	-0.07**	-0.07**

** Denotes statistically different from zero (t-test; $\alpha = 0.01$).
* Denotes statistically different from zero (t-test; $\alpha = 0.05$).

Table 5.7. Mean absolute residual in individual-tree dbh 12-year projections by dbh size classes. Values within a row followed by the same letter are not statistically different (α=0.05)[a] .

		Disaggregation Model		
dbh size class	n	D/S	BA Increment	BA Size
		------------ unthinned -------------		
All	4,113	0.57 a	0.54 b	0.53 b
Lower quartile	658	0.50 a	0.50 a	0.45 a
Inter-quartile	2,116	0.55 a	0.54 a	0.53 a
Upper quartile	1,339	0.65 a	0.57 a	0.56 a
		------------ thinned -----------		
All	11,468	0.61 a	0.59 b	0.59 ab
Lower quartile	798	0.65 a	0.65 a	0.61 a
Inter-quartile	5,833	0.60 a	0.59 a	0.58 a
Upper quartile	4,847	0.61 a	0.58 a	0.58 a

[a/] Distribution-free multiple comparision test based on Kruskal-Wallis rank sums (Miller 1966).

Table 5.8. Median residual in estimating the minimum, mean, and maximum individual-tree diameter for 12-year projections on unthinned and thinned plots.

	Dissagregation Model		
	D/S	BA Increment	BA Size
	--- unthinned (n=89) ---		
minimum	0.10**	0.20**	-0.10*
mean	0.03**	-0.00	-0.01**
maximum	-0.9**	0.10	0.10
	--- thinned (n=186) ---		
minimum	-0.20**	-0.30**	-0.40**
mean	-0.00	-0.02**	-0.02**
maximum	-0.30**	0.02**	0.10*

** Denotes statistically different from zero (sign test; $\alpha = 0.01$).
* Denotes statistically different from zero (sign test; $\alpha = 0.05$).

Differences in projected dbh distributions were also assessed in terms of yield estimates. For all trees in the observed and projected tree lists, individual tree height was estimated as (Zhang *et al.* 1997):

$$h = 1.4174\, H_d^{0.9397}\, e^{-0.7843\frac{1}{A} + \left(\frac{1}{d} - \frac{1}{d_{\max}}\right)\left(-3.0047 + 2.5291\left(\frac{\ln(N)}{A}\right)\right)} \qquad [5.17]$$

Total, product class yields (Table 5.9) per acre were estimated (Tasissa *et al.* 1997) for the observed and projected tree lists on unthinned stands as

$$tvol = 0.21949 + 0.00233\, d^2 h$$

and on thinned stands as

$$mvol = tvol\left[e^{-0.78579\left(\frac{d_t^{4.92060}}{d^{4.55878}}\right)}\right]$$

$$tvol = 0.25663 + 0.00239\,d^2 h$$

$$mvol = tvol\left[e^{-1.04007\left(\frac{d_t^{5.25569}}{d^{4.99639}}\right)}\right]$$

where

tvol = total volume (ft^3) outside bark,

mvol = merchantable volume (ft^3) outside bark,

d_t = top diameter merchantability limit (in) outside bark.

Analysis of Reynolds' *et al.* (1984) error index, using 1-inch dbh classes weighted by individual-tree volume, (Table 5.10) suggests there is little difference in the ability of the different disaggregation models to accurately project diameter distributions. Analysis of median percent error by product classes indicates the BA Increment and BA size models tend to be more accurate than the D/S model (Table 5.11). The tendency of the D/S model to over estimate maximum dbh on unthinned stands results in a comparatively large over estimate in sawtimber volume.

Table 5.9. Top diameter and dbh specifications for merchantable, pulpwood, and sawtimber size trees. All values are outside bark (inches).

	Minimum dbh	Maximum dbh	Top diameter
Merchantable	5.0	-	4.0
Pulpwood	5.0	9.5	4.0
Sawtimber	9.5	-	8.0

Table 5.10. Average error index for unthinned (n=89) and thinned (n=186) plots. Based on differences in the number of trees per 1-inch dbh class (weighted by total tree volume). Values within a row followed by the same letter are not statistically different (α=0.05)[a] .

	Dissagregation Model		
	D/S	BA Increment	BA Size
unthinned	1791.11 a	1596.79 a	1566.34 a
thinned	1161.97 a	1146.82 a	1122.25 a

[a/] Distribution-free multiple comparision test based on Kruskal-Wallis rank sums (Miller 1966).

Table 5.11. Median percent error in cubic-foot volume yield estimates by product class for 12-year projections on unthinned and thinned plots.

		Dissagregation Model		
Product Class	Plots	D/S	BA Increment	BA Size
		--- unthinned ---		
Total	89	1.3**	-0.2	0.1
Merchantable	89	1.4**	-0.2	-0.1
Pulpwood	89	4.7**	-1.1	-2.6
Sawtimber[a]	63	-9.8**	0.8	2.7*
		--- thinned ---		
Total	186	0.4**	-0.2	-0.1
Merchantable	186	0.4**	-0.3*	-0.2
Pulpwood	186	-3.7*	-3.5*	-6.6**
Sawtimber[a]	155	1.3	2.9**	3.1**

a/ Based on plots with at least 500 ft^3/ac of sawtimber volume.
** Denotes statistically different from zero (sign test; α = 0.01).
* Denotes statistically different from zero (sign test; α = 0.05).

Discussion

The slope of the linear relationship between relative growth rate and relative size is related to stand height, basal area, and to a lesser extent site quality. Utilizing stand height as a measure of time, as opposed to stand age, incorporates some of the effects of site quality. While site index improved the fit of the model with the Coop spacing study, the range of site index in this study is limited. When equation [5.14] was extrapolated to a wider range in site index, via the stand-level model TAUYIELD (Amateis *et al.* 1995), estimates of the slope coefficient were illogical. This suggests the site index range in the Coop spacing study is not sufficient to correctly model the effect of site index on the linear relationship between relative growth rate and relative size.

In general, for 12-year projections, the D/S disaggregation model performed slightly worse than the BA Increment and BA Size disaggregation models. The tendency to overestimate growth on the larger trees was the main weakness of the D/S model. In this study, the D/S model was derived assuming a linear relationship between relative growth rate and relative size. This approximation may account for the tendency of the resultant model to over predict dbh growth on the larger trees within a dbh distribution. A non-linear model of the relationship may have resulted in better estimates on the larger trees. However, inspection of the actual trends (Appendix A) does not suggest an obvious non-linear trend.

In previous applications of the BA Size model, the coefficient of the relative size relationship was reported to be constant over a range of stand ages and density (Pienaar and Harrison 1988, Borders and Patterson 1990). In this study, the coefficient varied with relative spacing and height. Much of the evidence for this relationship occurred with the Coop spacing study. The wide range in density and annual measurements may explain the trends reported here.

As stands approach crown closure and begin to compete for resources, larger trees have a competitive advantage over their smaller neighbors. It is reasonable to expect this advantage to increase at higher densities. With the D/S model and the BA Size model density is explicitly included in the estimation of the disaggregation function. With these models, larger trees receive proportionally more of the stand-level basal area growth as density increases. Incorporating a measure of density in the model to estimate the slope of the basal area increment line may further improve the BA Increment disaggregation model.

Conclusions

Based on the analysis of systematic changes in the dominance/suppression relationship with long-term remeasurement data, one can conclude:

- The slope of the linear relationship between relative growth rate and relative size (the dominance/suppression relationship) is a function of site height, density, and to a lesser extent, site quality.

- The slope of the dominance/suppression relationship can be used as the basis for a disaggregation model to distribute stand-level basal area growth over an initial tree list.