Results and discussion

Initial and projected mean per-hectare values for the 10 plots are shown in Table 1. The rankit plots indicated that replications for 9 of the 10 test plots followed a normal distribution. This suggested that the number of stochastic replications was sufficient for meaningful analysis. Subsequent analysis revealed that the slope and intercept coefficients were not significantly different from 1 and 0 at the 5% level, respectively; i.e., there was no significant difference between deterministic and stochastic estimated mean per-hectare values. There was also no significant difference in the range of tree diameters for the two mortality algorithms.

The K–S tests of the cumulative diameter distributions confirmed these results; there was no significant difference between deterministic and averaged stochastic distributions in 8 out of the 10 cases at the 5% level. These results are supported by those noted above for the range of diameters; however, the K–S test assumption of independence of observations (trees) in each sample (plot) is questionable here. The K–S test results should thus be interpreted as an index of agreement rather than as a rigorous statistical analysis. In any case, graphs of the deterministic and averaged stochastic distributions indicated little practical difference between them.

Close agreement was found for most of the plots, even for bimodal and trimodal distributions. The largest differences were found for the plots with the most irregular distribution shapes. A larger number of replications (more than 10) is probably needed to obtain a reliable average for the stochastic results in such situations.

These results confirm the effectiveness of deterministic mortality estimation techniques. Concern for efficiency in model usage further suggests use of deterministic mortality algorithms unless interest lies in studies of variability and related implications for forest stand development. However, it should be recognized that stochastic variation induced by the algorithm noted here may not estimate true stochastic variability well. The variation produced may be just an artifact of the procedure. Consideration of that possibility should temper the interpretation of stochastic model output.

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Use of crown ratio to improve loblolly pine taper equations

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VALENTI, M. A., and Q. V. CAO. 1986. Use of crown ratio to improve loblolly pine taper equations. Can. J. For. Res. **16**: 1141–1145.

Data from 278 trees felled in a loblolly pine (*Pinus taeda* L.) plantation were used to include crown ratio as a measure of tree form in a taper equation. The data were divided into 10 crown ratio classes. A segmented taper equation was fitted to each of the 10 classes to detect trends in the coefficients. Coefficients were then expressed as functions of crown ratio. The resulting three-segment taper equation with crown ratio as an additional independent variable was more flexible and provided more accurate predictions of upper stem diameters. Similar techniques were used to include crown ratio in a two-segment taper equation. The three-segment equation fitted the data better than the two-segment equation and provided superior taper predictions for the test data set.

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Des données provenant de 278 arbres abattus dans une plantation de *Pinus taeda* L. ont servi à mesurer le rapport de cime comme évaluation de la forme de l'arbre dans une équation de défilement. Les données furent divisées en 10 classes de rapport de cime. Une équation de défilement par segments a été appliquée à chacune des 10 classes en vue de déduire les tendances au niveau des coefficients. Ces coefficients ont par la suite été exprimés sous la forme de fonctions du rapport de cime. L'équation de défilement par segments qui en est résulté, ayant le rapport de cime comme variable indépendante additionnelle, était plus flexible et offrait des prédictions plus précises des diamètres à la partie supérieure de la cime. On a employé des techniques semblables pour l'inclusion du rapport de cime dans une équation de défilement à deux segments. L'équation à trois segments a mieux convenu aux données que celle à deux segments et a procuré de meilleures prédictions du défilement à partir des données provenant de l'échantillon.

[Traduit par la revue]

Introduction

Taper curves provide valuable information to practicing foresters. A tree with a less rapid taper can yield as much as 20% more volume than a tree of comparable size having more taper (Heger 1965). A simple measure of form, such as crown ratio (CR), in a taper equation would be expected to improve the estimate of stem taper (Bruce et al. 1968; Matney and Sullivan 1979).

Dell et al. (1979) found that in fitting a general model for trees of different CR classes, a pattern of change occurred in some of the coefficients. They employed a separate taper equation for each of three CR classes in their growth and yield model for slash pine plantations. Feduccia et al. (1979) and Baldwin and Polmer (1981) applied this idea to loblolly pine and longleaf pine plantations, respectively, and obtained similar results. Fries (1965) sorted his data into five crown length groups. His eigenvector analysis revealed a significant difference in taper between the five groups. Dell (1979) believed that CR could be easily included in field measurements and discussed the potential of using CR in refining stem taper curves.

Matney and Sullivan (1979) demonstrated that a loblolly pine taper model constrained to pass through an upper stem diameter can yield more precise estimates of taper and volume than models not similarly constrained. Their results indicated that models with additional predictor variables can increase the precision of taper estimates. CR was related to parameters of several loblolly pine taper models in a study by Burkhart and Walton (1985). However, they found that the relationship was not sufficiently strong to justify the inclusion of CR as a predictor variable in the taper equations.

The objective of this study was to investigate the possibility of including CR as a measure of tree form in a taper equation for loblolly pine to improve diameter estimates.

Data

Data collected from a loblolly pine plantation at the Hill Farm Research Station, Homer, LA, were used in this study. Twenty 0.5-acre (1 acre = 0.405 ha) blocks, each with a 0.25-acre measurement plot, were established in 1958 with seedlings planted at a 6 × 6 ft (1 ft = 0.305 m) spacing. Site index ranged from 61 to 76 ft (base age, 25 years) for the study area. From 1962 to 1965, the plots were thinned to 1000, 600, 300, 200, and 100 trees per acre (TPA) in a stepwise thinning procedure. Four plots were thinned to 1000 TPA and the remaining 16 plots were thinned to 600 TPA. When a 0.1-in. (1 in. = 2.54 cm) difference in average diameter was detected between the 1000 and 600 TPA plots, twelve of the sixteen 600 TPA plots were thinned to 300 TPA. The same method was carried out for the 200 and 100 TPA treatments. By 1965 (age 7 years) the stepwise thinning was complete.

The plots were thinned again in 1978 at age 21 years. Measurements from 278 trees felled in the 1978 thinning were used in this study. Diameter outside bark and bark thickness were taken at 25-in. intervals starting from the stump to the tip of the tree. Diameter at breast height (dbh), total height, and height to the live crown were also recorded. Diameter and height were measured to the nearest 0.1 in. and 0.1 ft, respectively. The ranges of dbh, total height, and CR of the 278 trees felled at age 21 years are presented in Table 1. There was a total of 6360 diameter measurements.

Procedures and methods

Taper models comprising a single function fail to accurately estimate butt swell and tree tip; they tend to underestimate taper in the lower bole and overestimate taper in the upper bole. These shortcomings can be overcome by describing various sections of the tree with different submodels and then joining them together to form a segmented model. Three-segment models generally provide more accurate estimates of stem form than estimates obtained from one- or two-segment models. The three-segmented taper equation introduced by Max and Burkhart (1976) was recommended by Cao et al. (1980) for describing stem profile. Thus, this flexible model was selected as the basic equation in this study. The three-segment taper equation can be rewritten in the following modified form:

$$[1] \quad d^2 = D^2(b_1 z + b_2 z^2 + b_3(z - a_1)^2 I_1 + b_4(z - a_2)^2 I_2)$$

where d is the diameter inside bark in inches at any given height h, D is the diameter at breast height in inches, z equals $1 - (h/H)$, h is the height in feet above the ground, H is the total tree height in feet, b_i represents the regression coefficients estimated from the data (i = 1, 2, 3, 4), a_i represents the join points estimated from the data (i = 1, 2), and I_i equals 1, if $z > a_i$ (i = 1, 2), or 0, otherwise.

The data were divided into 10 CR classes, each with an approximately equal number of observations. Equation 1 was fitted separately to each CR class and the resulting coefficients were plotted against the CR class medians to detect trends. Based on these plots, some of the coefficients were expressed as a function of CR.

Replacing some coefficients with functions of CR resulted in many taper equations with CR as an additional independent variable. The criteria used in this study for selecting the "best" model included the following statistics: (*i*) percent variation explained by the model, $1 - \Sigma(y_i - \hat{y}_i)^2/\Sigma(y_i - \bar{y})^2$, (*ii*) bias, $\Sigma(y_i - \hat{y}_i)/n$, and (*iii*) absolute bias, $\Sigma|y_i - \hat{y}_i|/n$, where y_i and $\hat{y}_i$ are the observed and predicted diameter inside bark for the i^{th} observation, respectively, and n is the number of observations.

The data were randomly divided into two groups, a fit data set and a test data set (approximately 75 and 25% of the total number of observations, respectively). The fit data set was used to estimate the coefficients of the taper models. The above statistics generated by the fit data set showed how well the models fit the sample data. The models were then validated using the test data set. Statistics from this data set gave an indication of how well the models predict for the population. The choice for the "best" taper equation was based on the ranking of the above three criteria.

Results and discussion

Figure 1 shows that the largest and smallest of the 10 CR classes differed in stem form. As expected, trees with larger CRs tapered more than those with smaller CRs. Most of the difference occurred in the upper portion of the bole, above the

TABLE 1. Range of data from 278 loblolly pine trees felled at age 21

dbh class (in.)	Total height (ft)			CR (no. of trees)							
	Min.	Mean	Max.	0.20	0.30	0.40	0.50	0.60	0.70	0.80	Total
4	47	47	47		1						1
5	42	53	59	3	2	1					6
6	30	51	62	5	15	6	1				27
7	25	52	67	6	17	24	1	1	1		50
8	29	56	72	5	21	17	4	3	1		51
9	42	59	73		8	21	15	1			45
10	50	61	71		6	7	11	5			29
11	50	61	69	1	1	4	12	5	2		25
12	50	64	77			7	9	3	2	1	22
13	54	62	65				4	2	1		7
14	52	64	72			2	2	4	1	1	10
15	63	68	72			2	1	1			4
16	72	72	72					1			1
Total				20	71	91	60	26	8	2	278

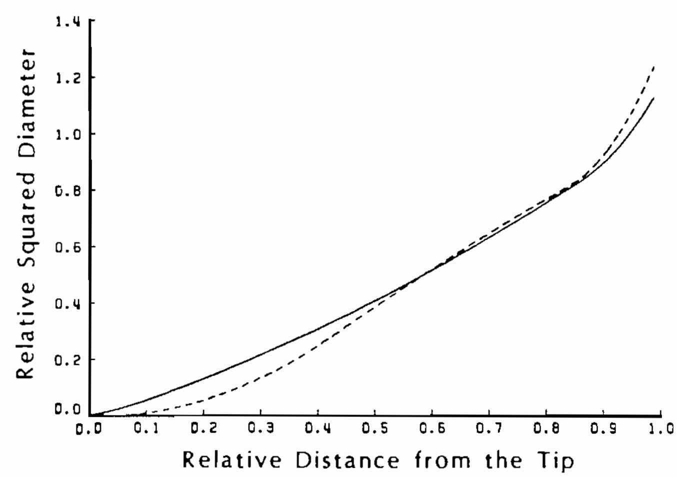

FIG. 1. Stem profiles of the smallest (—) and largest (----) classes of CR. Parameters of the three-segment taper equation were fitted separately to each of the CR classes.

upper join point (a_1) defined in the model. Expressing the upper bole parameters (a_1, b_1, and b_2) as a function of CR should account for this variation.

Plotting the parameters of Eq. 1 against the medians of the CR classes revealed that a relationship existed between the a_1 and b_1 parameters and CR. Since Eq. (1) already contained 6 parameters, the number of additional parameters was kept to a minimum. The following functions were examined: (*i*) linear, $c_0 + c_1\text{CR}$, (*ii*) hyperbola, $c_0 + c_1/\text{CR}$, and (*iii*) logarithm, $c_0 + c_1 \ln \text{CR}$. The a_1 and b_1 coefficients in Eq. 1 were replaced with combinations of the above functions. The model with $b_1 = c_0 + c_1/\text{CR}$ and $a_1 = c_2 + c_3 \ln(\text{CR})$ was selected because of its superior performance on all three criteria for both fit and test data sets (Table 2). The resulting taper equation has the following form:

$$[2] \quad d^2 = D^2[(c_0 + c_1/\text{CR})z + b_2z^2 + b_3(z - (c_2 + c_3 \times \ln(\text{CR}))^2 I_1 + b_4(z - a_2)^2 I_2]$$

where I_1 equals 1, if $z > c_2 + c_3 \ln(\text{CR})$, or 0, otherwise, and I_2 equals 1, if $z > a_2$, or 0, otherwise.

An F-test was performed to determine whether CR improves the accuracy and precision of the taper equation by comparing Eqs. 1 and 2. This method for comparing two nonlinear equations is the same method used to compared two liner models. The approximated F value for this test is fairly accurate (Gallant 1975). The test resulted in an F value of 88, which is significant at the 5% probability level.

The medians of the smallest and largest 10 CR classes were used as values for CR in Eq. 2 to construct curves shown in Fig. 2. These curves look similar to those in Fig. 1, indicating that Eq. 2 is sufficiently flexible to describe stem forms for a wide range of CRs.

In an attempt to reduce the number of parameters (eight in Eq. 2), the two-segment quadratic model (Max and Burkhart 1976) was also considered:

$$[3] \quad d^2 = D^2(b_1z + b_2z^2 + b_3(z - a_1)^2 I_1)$$

where I_1 equals 1, if $z > a_1$, or 0, otherwise.

Similar techniques for incorporating CR as an additional independent variable were employed for the two-segment taper model. The following equation form, where $b_1 = c_0 + c_1/\text{CR}$ and $b_2 = c_2 + c_3/\text{CR}$, was selected because it performed best on both fit and test data sets (Table 3):

$$[4] \quad d^2 = D^2[(c_0 + c_1/\text{CR})z + (c_2 + c_3/\text{CR})z^2 + b_3(z - a_1)^2 I_1]$$

where I_1 equals 1, if $z > a_1$, or 0, otherwise.

Table 4 shows Eq. 1–4 with parameters estimated from all data (fit and test data sets combined).

From a biological standpoint, the relationship in Eq. 2 between parameters a_1 and b_1 of Eq. 1 and CR seems reasonable. The upper join point (a_1) is located at the point of inflection near the base of the crown. As CR increases, the value of the upper join point also increases. The shifting of this join point and the inclusion of CR in the first segment of Eq. 1 in terms of b_1 resulted in a more flexible taper model. Burkhart and Walton (1985) did not consider the possibility of this combination; this may be one reason why they were unable to use CR to improve the accuracy and precision of taper equation estimates. For the two-segment model, the single join point is located near the butt swell and, thus, both parameters b_1 and b_2 of Eq. 3 needed to be expressed as functions of CR, which was accomplished in Eq. 4.

TABLE 2. Evaluation of three-segment taper equations with and without CR

Model	Fit data set (n = 4769) % variation explained by the model	Fit data set Bias*	Fit data set Absolute bias†	Test data set (n = 1591) % variation explained by the model	Test data set Bias*	Test data set Absolute bias†
$d^2 = D^2(b_1z + b_2z + b_3(z - a_1)^2I_1 + b_4(z - a_2)^2I_2)$	96.61	0.0222	0.3812	96.36	0.0149	0.3815
Replace b_1 with $c_0 + c_1$/CR	96.58	0.0315	0.3837	96.33	0.0245	0.3833
Replace a_1 with $c_0 + c_1$CR	96.62	0.0320	0.3819	96.38	0.0253	0.3816
Replace a_1 with $c_0 + c_1$ ln (CR)	96.63	0.0334	0.3816	96.41	0.0268	0.3800
Replace b_1 with $c_0 + c_1$CR and replace a_1 with $c_2 + c_3$CR	96.85	0.0152	0.3663	96.61	0.0101	0.3656
Replace b_1 with $c_0 + c_1$/CR and replace a_1 with $c_2 + c_3$ ln (CR)	96.90	0.0011	0.3619	96.71	−0.0054	0.3592

*Bias = $\Sigma \text{Diff}_i/n$, where Diff_i is the observed minus predicted diameter inside bark for the ith observation.
†Absolute bias = $\Sigma|\text{Diff}_i|/n$.

TABLE 3. Evaluation of two-segment taper equations with and without CR

Model	Fit data set (n = 4769) % variation explained by the model	Fit data set Bias*	Fit data set Absolute bias†	Test data set (n = 1591) % variation explained by the model	Test data set Bias*	Test data set Absolute bias†
$d^2 = D^2(b_1z + b_2z^2 + b_3(z - a_1)^2I)$	95.92	−0.0533	0.4178	95.55	−0.0624	0.4171
Replace b_1 with $c_0 + c_1$CR	95.90	−0.0433	0.4193	95.53	−0.0522	0.4173
Replace b_2 with $c_0 + c_1$CR	95.91	−0.0408	0.4187	95.56	−0.0493	0.4160
Replace a_1 with $c_0 + c_1$CR	95.92	−0.0508	0.4176	95.56	−0.0595	0.4159
Replace b_1 with $c_0 + c_1$CR and replace b_2 with $c_2 + c_3$CR	96.06	−0.0637	0.4108	95.71	−0.0721	0.4083
Replace b_1 with $c_0 + c_1$/CR and replace b_2 with $c_2 + c_3$/CR	96.07	−0.0673	0.4095	95.72	−0.0750	0.4073

*Bias = $\Sigma \text{Diff}_i/n$, where Diff_i is the observed minus predicted diameter inside bark for the ith observation.
†Absolute bias = $\Sigma|\text{Diff}_i|/n$.

TABLE 4. Four taper equations (with and without CR) with coefficients estimated from all 278 loblolly pine trees (6360 diameter measurements) felled at age 21 years

Equation No.	Equation
1	$d_2 = D^2(0.0172z + 1.6675z^2 - 1.6729(z - 0.3524)^2I_1 + 14.2099(z - 0.8622)^2I_2)$ where $I_1 = \begin{cases} 1, \text{if } z > 0.3524 \\ 0, \text{otherwise} \end{cases}$ and $I_2 = \begin{cases} 1, \text{if } z > 0.8622 \\ 0, \text{otherwise} \end{cases}$
2	$d^2 = D^2[(-0.2113 + 0.0962/\text{CR})z + 1.7419z^2 - 1.7313(z - (0.4411 + 0.1346 \ln \text{CR}))^2I_1 + 14.4538(z - 0.8636)^2I_2]$ where $I_1 = \begin{cases} 1, \text{if } z > 0.4411 + 0.1346 \ln \text{CR} \\ 0, \text{otherwise} \end{cases}$ and $I_2 = \begin{cases} 1, \text{if } z > 0.8636 \\ 0, \text{otherwise} \end{cases}$
3	$d^2 = D^2(0.4140z + 0.6565z^2 + 19.4201(z - 0.9020)^2I_1)$ where $I_1 = \begin{cases} 1, \text{if } z > 0.9020 \\ 0, \text{otherwise} \end{cases}$
4	$d^2 = D^2[(0.1862 + 0.1041/\text{CR})z + (0.9775 - 0.1468/\text{CR})z^2 + 19.8050(z - 0.9026)^2I_1]$ where $I_1 = \begin{cases} 1, \text{if } z > 0.9026 \\ 0, \text{otherwise} \end{cases}$

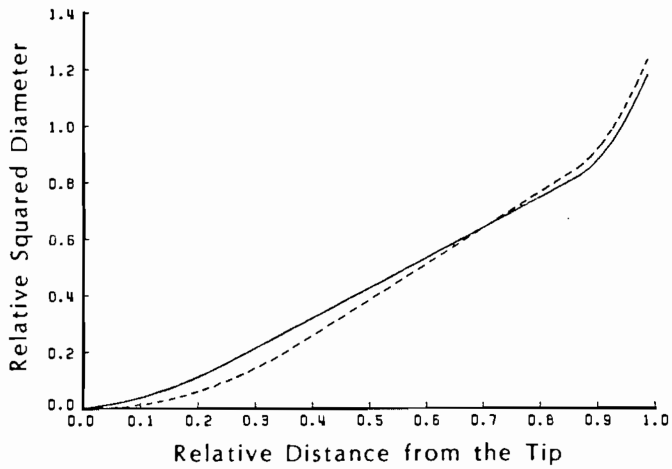

FIG. 2. Stem profiles of the smallest (—) and largest (----) classes of CR using the three-segment taper equation with CR as an additional variable.

Statistics from Tables 2 and 3 show that the three-segment model (Eq. 2) fits the data better and provided superior predictions for the test data set. Equation 2 explained more of the variation, had less bias, and had a lower mean absolute difference.

The two-segment model tended to underestimate the middle section of the bole and overestimate the upper section. The reduction in number of estimated parameters (from eight in Eq. 2 to six in Eq. 4) also resulted in a decrease in the predictive capability of the taper model.

Parameter estimates for the four equations (Table 4) are limited to the loblolly pine data used in this study. However, the techniques presented here can be applied to both thinned and unthinned stands of other single-stemmed coniferous species.

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Impact of feeding damage by snowshoe hares on growth rates of juvenile lodgepole pine in central British Columbia

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SULLIVAN, T. P., and D. S. SULLIVAN. 1986. Impact of feeding damage by snowshoe hares on growth rates of juvenile lodgepole pine in central British Columbia. Can. J. For. Res. **16**: 1145–1149.

This study assessed the impact of snowshoe hare (*Lepus americanus* Erxleben) feeding injuries on diameter and height growth of juvenile lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.). Five-year growth increments of undamaged and damaged crop trees in control (unspaced) and spaced stands, 20 km east of Prince George, B.C., were compared using analysis of variance. Semigirdling (sublethal) damage clearly suppressed diameter growth of small diameter (control, 41–60 mm; spaced, 31–50 mm) trees, but had little effect on larger stems. Height increment was significantly reduced by semigirdling in all diameter classes except for the 61–80 mm class in the control. Surface area or amount of bark and vascular tissue removed had little effect on growth increments in the spaced stand. The recommendation to delay spacing until the average tree diameter is >60 mm to avoid snowshoe hare damage is further supported for diameter but not necessarily for height growth.

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