PREDICTION OF FINAL SWEEP IN PRUNED *PINUS RADIATA* LOGS FROM JUVENILE SWEEP MEASUREMENTS

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ABSTRACT

The relationship between juvenile and final stem sweep is used to aid selection of final-crop trees at time of thinning, and measurement of juvenile sweep at final pruning (approximately age 6 to 8 years) provides the information with which to predict sweep in the final-crop stems of *Pinus radiata* D. Don stands. Sweep in the pruned butt log, in conjunction with log diameter, length, and taper, affects the level of conversion to sawn timber, and hence, the value of a log. Pith sweep, as a surrogate for juvenile sweep, and final-stem sweep data calculated from cross-sectional analyses or sawing studies of 815 pruned logs, were used to improve the stand average and individual log sweep predictions made in the stand modelling system STANDPAK. The following juvenile / final sweep model was fitted using regression analysis:

$$S_F = aS_P - b(AGE\text{–}28)$$

where: S_F is final sweep (mm/m)
S_P is pith sweep (mm/m)
AGE is time from juvenile sweep measurement to final harvest (years)
a, b are regression coefficients .

Validation by residual analysis indicated the model slightly under-predicted final sweep and the error in predicting final sweep could be expected to fall within ±5 mm/m. Comparison of the fit of several distribution models to study data, by comparing chi-squared goodness-of-fit deviances, identified the lognormal distribution as a reliable predictor of individual log final sweep. Validation using an independent data set from six sites indicated the error in predicting percentage frequency of logs in individual log classes could be expected to fall within ±20%. An important limitation of this study was the use of pith sweep as a surrogate for juvenile sweep.

Keywords: juvenile sweep; pith sweep; mature sweep; regression model; distribution model; STANDPAK; *Pinus radiata.*

INTRODUCTION

Selection of final-crop trees on the basis of sweep, and the accurate prediction of sweep in pruned logs at maturity, are important if the value of a final crop is to be maximised. Measurement of juvenile sweep at final pruning, and knowledge of the relationship between this measured juvenile sweep and mature sweep, will provide information which can be used to guide tree selection criteria (Maclaren 1995) and predict final-crop value. Sweep in the pruned butt log has an important impact on the value of pruned logs (Cown *et al.* 1984); in conjunction with log diameter, length, and taper, it affects the level of conversion of a log to sawn timber which in turn influences log value (MacDonald & Sutton 1970; Cown *et al.* 1984; Gosnell 1987). In a study of timber recovery from *Pinus radiata* pruned butt logs (Cown *et al.* 1984) the average log values* for moderately (11–20 mm/m) and severely (>20 mm/m) swept logs dropped by 18% and 33% respectively compared with straight logs (<10 mm/ m). Log size has an important influence on the extent to which sweep devalues logs, with increasing diameter compensating for the loss of value for a given degree of sweep (Cown *et al.* 1984). Sawn timber defects which arise from sweep, such as sloping grain, compression wood, and pith defects, also reduce pruned log value (Fielding 1940; Nicholls 1982; Cown 1992).

Two factors have the potential to influence the relationship between juvenile sweep and sweep in the mature pruned log—

- stem diameter, as represented by small-end diameter (s.e.d.), large-end diameter (l.e.d.), or diameter at breast height (dbh = stem diameter over bark at 1.4 m), and
- age.

These factors affect the amount of stem growth that has masked juvenile sweep. Whether this is an influence on the relationship between juvenile and stem sweep depends on the mechanism by which trees improve stem form. Jacobs (1938) suggested that sweep simply becomes less noticeable with time since the increasing stem diameter makes any stem deviation a smaller proportion of the diameter. A second mechanism, identified by Dadswell & Wardrop (1949), is the effect of development of reaction wood on stem form improvement. Another factor in the improvement of stem form is the result of differential radial growth (Schlesinger 1972; Miller 1974; Cremer 1998), with greater stem growth on the inside of the swept stem.

Prediction of mature sweep in the stand modelling system STANDPAK (Whiteside *et al.* 1989) is a two-stage process; firstly, the average pruned log sweep of a stand is estimated from the relationship between juvenile and mature sweep. Secondly, using the estimated stand average sweep, individual log sweep is calculated from an exponential distribution of log sweep.

Stand Average Final Sweep

STANDPAK presently predicts stand average sweep at harvest using a linear relationship between juvenile sweep and final log sweep (Eq. 1) developed from sweep measurements on 135 trees from six sites (N.J.Woods & J.D.Tombleson unpubl. data).

$$S_F = aS_J + b \qquad r^2 = 0.55 \qquad \text{[Eq. 1]}$$

where: S_F is final sweep (mm/m)

S_J is juvenile sweep (mm/m)

a, b are regression coefficients.

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* Log values ($\$/m^3$ round) were calculated using Whiteside's (1982) Price List B and include a credit of $\$12.50/m^3$ for sawmill residues (Cown *et al.* 1984).

Individual Log Final Sweep

Individual log sweep within STANDPAK is estimated from the stand average stem sweep using an exponential distribution. The proportion of swept logs and the mean sweep of those logs are then calculated based on the sweep limits defined in log grading rules.

The availability of new data from the assessment of pruned logs (Somerville 1985; Park 1987) provides the opportunity to further improve prediction of stand average and individual log sweep. Additional log parameters (dbh, s.e.d., l.e.d., and age) were also incorporated into the data set to explore the effect of these variables on final sweep prediction.

MATERIALS AND METHODS

Database

Final log and pith sweep data used in this study were derived from pruned log assessments made at 19 sites (Fig. 1) using either sawing studies (Park 1987) or cross-sectional analysis (Somerville 1985). Both methods require log measurements prior to breakdown, and defect measurements (e.g., pith, branches) after breakdown. The primary difference between them is the breakdown method—transverse in sawing studies, and longitudinal in cross-sectional analysis.

Selection of logs for measurement by the sawing study method (Park 1987) was based on achieving a sample which was representative of the pruned element in a stand, in terms of diameter, pruned length, log defects, and stem straightness. In order to be processed at a sawmill, logs were required to have a s.e.d. of at least 25 cm, and a maximum stem deviation no greater than 17 cm. Selection of logs for measurement by cross-sectional analysis (Somerville 1985) was based on sweep, with straight peeler logs being selected (A.Somerville pers. comm.). At the Woutu site, where logs were selected randomly, the logs were more swept on average than logs measured at other sites (Table 1). The selection of straight logs

FIG. 1–Location of stands for which pruned log assessments were made.

TABLE 1–Percentage of logs by location, with final sweep occurring in each sweep class: straight, moderate, and severe.

Location	Percentage of logs in sweep class		
	Straight (<10 mm/m)	Moderate (11 to 20 mm/m)	Severe (>20 mm/m)
Berwick	67.8	32.2	0.0
Esk	66.7	33.3	0.0
Woutu	12.5	62.5	25.0
Golden Downs	81.8	18.2	0.0
Gwavas	91.7	8.3	0.0
Herbert	100.0	0.0	0.0
Kaingaroa	90.5	9.5	0.0
Kinleith	72.7	27.3	0.0
Mangatu	77.4	22.6	0.0
Mohaka	80.0	20.0	0.0
Ngatira	86.7	13.3	0.0
Ngaumu	70.5	22.7	6.8
Otago Coast	76.5	22.0	1.5
Patunamu	92.9	7.1	0.0
Rai Valley	70.0	30.0	0.0
Rankleburn	92.5	7.5	0.0
Taupo	90.4	9.6	0.0
Waiuku	100.0	0.0	0.0
Waratah	66.7	33.3	0.0

for measurement by both methods may result in a bias in the data set in favour of straighter logs than represented by the stands as a whole. Sweep assessments made by S.A.Grallelis & B.K.Klomp (unpubl. data) in a Kaingaroa spacing and thinning trial identified a level of sweep similar to the data used in this study (Table 1 and Appendix 1). Sweep ranged from 0 to 21 mm/m, with an average sweep of 3 mm/m for all trees, including nominally straight trees (Grallelis & Klomp unpubl. data). Using the broad sweep classes devised by Cown *et al.* (1984), the majority of logs in the data set at each site were identified as straight, with only a few being classed as severely swept (Table 1).

The program to determine the maximum pith sweep for each log used three-dimensional reconstructions of individual logs for which data had been acquired by either sawing studies (Park 1987) or cross-sectional analysis (Somerville 1985). The external under-bark log profile was represented by a number of elliptical cross-sections, each of which had a uniquely defined centre, radii, and orientation. Within the log, the pith wandered along the entire length, independent of the central axis of the log (Todoroki 1997).

Pith sweep was measured in both the horizontal and the vertical planes, assuming the log length extended in a longitudinal direction. In each plane, a line extending from the pith at either end of the log was constructed and the deviation of the measured pith points, from this line, was calculated. Maximum pith sweep (mm/m) was defined as the maximum measured deviation divided by the log length (Fig. 2). Maximum final log sweep (mm/m) was determined in a similar manner with lines constructed in two planes that joined the centres of the log end cross-sections, which were assumed to be elliptical, and the deviation from the centre of each measured log cross-section ellipse was calculated. Maximum log sweep was

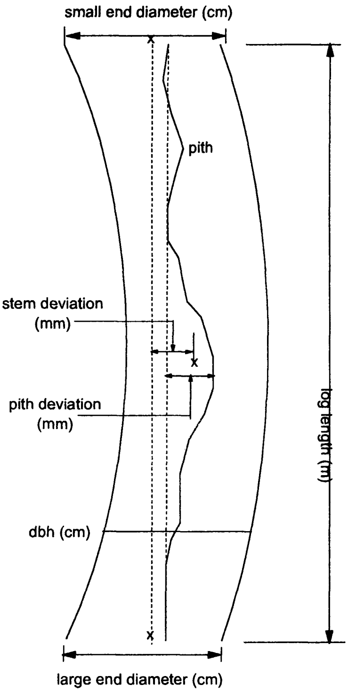

FIG. 2–The centre-to-centre method of stem and pith sweep estimation.

defined as the maximum measured deviation divided by the log length (Fig. 2). The position on the stem of the measured maximum pith and stem deviations was also calculated to determine if these positions coincided.

Pith deviation may be the result of sweep, or of kinks resulting from leader damage and subsequent recovery. The maximum pith deviation calculated, therefore, may arise from either of these processes. Logs for which maximum pith deviation resulted from kink were not considered in this study as it was felt pith kink was not representative of the juvenile sweep that might be measured at final pruning. It was assumed that if maximum pith deviation arose from sweep then the position of maximum pith deviation measured would coincide with the position of maximum external deviation measured. Positions were allowed to vary by 5 cm to allow for measurement error. Visual assessment of stem plots of a number of logs suggested this assumption was valid. For developing the relationship between pith and final sweep, only those logs for which the position of maximum pith and external sweep coincided were used (Appendix 1). Fitting of distributions for predicting individual log sweep utilised the entire data set (Appendix 2).

One failing of this selection method, however, was that the majority of logs assessed using the sawing study method were discarded from the data set. The limited number of external stem deviation measurements made using the sawing study method meant that there was a low likelihood of the maximum external stem deviation measurement coinciding with the maximum pith deviation measured.

At sites where there were a sufficient number of logs, the data were divided into "sample" sets and "validation" sets by randomly selecting approximately 50% of logs from each site. Summary statistics for the data sets are contained in Appendices 1 and 2. The "validation" set was used to validate the accuracy and precision of the model developed using the sample set. The data selected for the validation data set were not fully independent, in that logs from the same forest were also used to form the model. All data from two forests (Ngatira and Patunamu) were therefore excluded from the "sample" data set and used to provide independent data for validation.

ANALYSIS

Stand Mean Final Sweep

The variables that were identified, from a review of literature, as potentially influencing the relationship between pith sweep and final sweep were stand age and log diameter (dbh, s.e.d., l.e.d.). The importance of these variables in prediction of final sweep was tested using analyses of variance (ANOVAs) performed with PROC GLM in the SAS system (SAS Institute 1988). Each ANOVA included pith sweep, the "variable" being explored (i.e., age or diameter), and their interaction. The ANOVA, therefore, tested a model of the form:

$$y_i = \beta_0 + \beta_{11}x_{1i} + \beta_{21}z_{1i} + \beta_{1z}x_{1i}z_{1i} + \varepsilon_i$$

where significance of β_{21} tests for separate intercepts for z_{1i} (age, dbh, s.e.d., l.e.d.), and β_{1z} tests for separate slopes for z_{1i} (Myers 1990) where x_{1i} is pith sweep and y_i is final sweep. By including, for example, diameter in the model, the test for separate intercepts allows the mean final sweep to be β_2 lower than the mean final sweep for a smaller diameter log with the same pith sweep (Myers 1990). The test for separate slopes tests the assumption of additivity (Myers 1990), i.e., the effect of pith sweep on final sweep is the same for all, for example, diameters.

Stepwise regression, which allows for multi-collinearity among regressor variables, was performed using PROC STEPWISE in SAS with the STEPWISE option and significance levels for a variable to enter and stay in the model set at 15% (SAS Institute 1986). A high significance level ($p=0.15$) was used to prevent the stepwise algorithm from stopping short. The models produced in the early stages of the stepwise regression were often under-specified, resulting in variance being over-estimated. The tendency to terminate sooner can result in important variables not entering due to deflation of the F-statistics (Myers 1990).

The regression model from the stepwise regression results was assessed for prediction ability and goodness-of-fit using the root mean square error (RMSE), and coefficient of determination (r^2) derived from PROC REG output in SAS (SAS Institute 1986). To enable the application of the regression model to various sites, differences in model parameters among sites were explored by plotting parameter estimates and their associated standard errors for the model form fitted to individual sites. Six locations were excluded from the data set for this analysis due to a lack of data: Woutu, Herbert, Kinleith, Mohaka, Rai Valley, and Waratah. An ANOVA incorporating a location effect was also performed to test for the influence of location on the pith/final sweep relationship. The model was then validated using the "validation" data set by plotting residuals against predicted and independent variable values in the models. This allowed bias in the model to be identified.

Individual Log Final Sweep

Several distributions—exponential, normal, lognormal, and Weibull—were fitted to the sample data set. The lognormal distribution with a location parameter estimated was not tested as it is not possible to have negative sweep, and it was reasonable to assume that, for the level of accuracy used to measure sweep in this study, no logs in a stand will be absolutely straight.

Each distribution was individually fitted to the data from each location. The fit of each distribution was compared using deviances from the chi-squared goodness-of-fit test for the unknown parameter case (Bain & Engelhardt 1992) calculated by the DISTRIBUTION statement in GENSTAT (Genstat 5 Committee 1993). To enable easy comparison of fitted distributions among locations, the same number of groupings of logs was used to fit distributions to data from each location, regardless of the sample size, using the NGROUPS option. The average sample size for locations was 40 logs; therefore, the number of groupings was set to $\sqrt{40} \approx 6$. While the setting of classes to the same level has the advantage that deviance values can be easily compared, the disadvantages are that for locations with a small sample size some groups may have less than five observations (logs), resulting in unreliable results from the chi-squared goodness-of-fit test (Bain & Engelhardt 1992). Setting the number of groupings of logs also has the disadvantage that some information is lost by using grouped data rather than individual observations, resulting in less-accurate parameter estimates. Data from Woutu (eight logs), Herbert Forest (14), Mohaka (five), and Rai Valley (10) were excluded from the data set for fitting distributions because the number of logs measured at these locations was too small to allow distributions to be reliably fitted. To enable the application of the individual location distribution models to other sites, differences in model parameters among sites were explored by plotting parameter estimates and their associated standard errors. Differences in parameter estimates among locations were related to site variables such as site index, selection ratios, and mean sweep. The individual log sweep model was validated with logs from the "validation" data, set using residual analysis, by plotting actual sweep values against residuals (actual – predicted).

RESULTS AND DISCUSSION

Prediction of Stand Mean Final Sweep

Three parameters were identified as having the potential to influence the prediction of final stem sweep.

Pith sweep

There appeared to be a moderately strong linear relationship between final sweep and pith sweep (Fig. 3) with an r^2 of 0.74 and a RMSE of 2.10. Several logs (those points above the final sweep = pith sweep line in Fig. 3) stood out as having unusually high final sweep for their pith sweep (Fig. 3). These logs appeared to have greater final sweep than pith sweep, possibly due to wind damage resulting in bending of the stem after the pith had been set, though the logs came from several different sites.

Stem diameter

A paired t-test performed on the deviation of the pith and the stem (in millimetres), independent of log length, identified a significant difference ($p=0.01$) in pith and stem deviation with stem deviation being on average 81% that of pith deviation. This result suggests that a decrease in sweep associated with increasing diameter is not due to the mechanism described by Jacobs (1938). Increasing stem diameter resulting in stem deviation

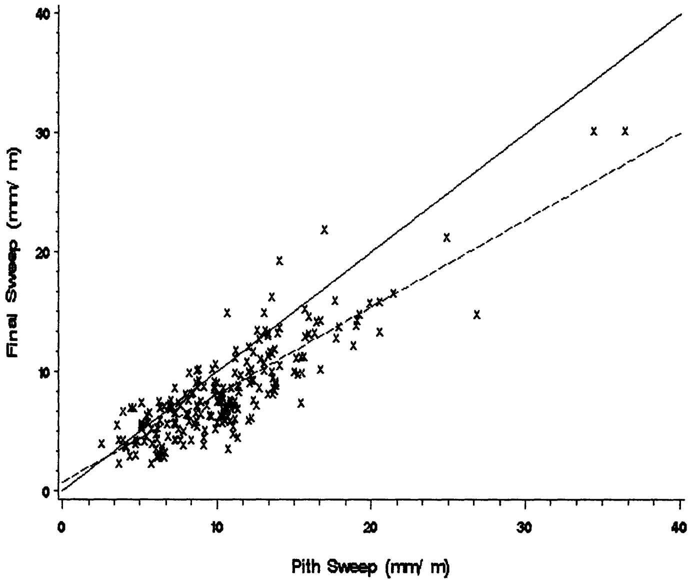

FIG. 3—Final sweep plotted against pith sweep with a linear trend line fitted (dashed line) to the "sample" data set. The line of final sweep = pith sweep (solid line) is also plotted.

becoming a smaller proportion of the diameter is not likely to be the only mechanism leading to reduced sweep with age.

The plot of pith sweep against final sweep by diameter (dbh) class showed no clear pattern in the relationship between final sweep and pith sweep, associated with log diameter (Fig. 4).

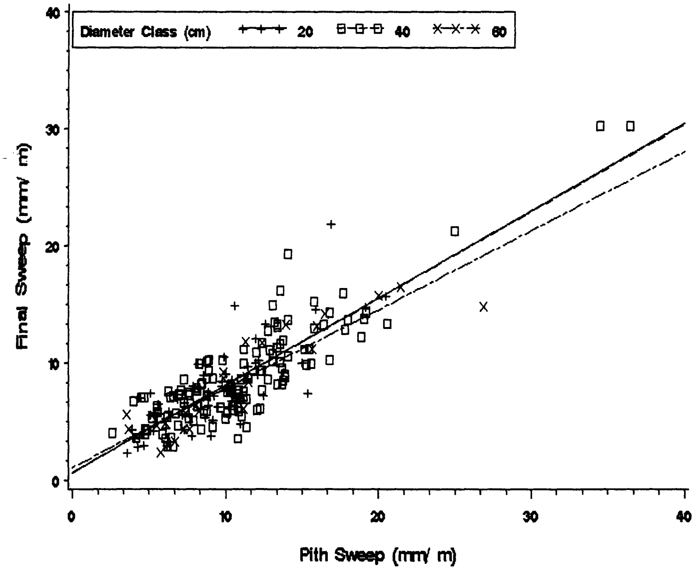

FIG. 4—Pith and final sweep data, with linear regression trend lines fitted for three diameter-at-breast-height (dbh) classes.

An analysis of variance (ANOVA) exploring the effect of pith sweep and diameter on final sweep identified pith sweep alone as all having a significant (p=0.01) effect on final sweep. The same results were found when small-end diameter and large-end diameter were used instead of diameter at breast height. The model fitted had an r^2 of 0.76 and a RMSE of 2.11. As the diameter and interaction effects were not significant ($p > 0.05$), this suggests that there are no separate regression intercepts or slopes for different levels of log diameter.

Age

The plot of pith sweep against final sweep, by age-class, showed a slight pattern of higher levels of final sweep, for a given level of pith sweep, with decreasing age (Fig. 5).

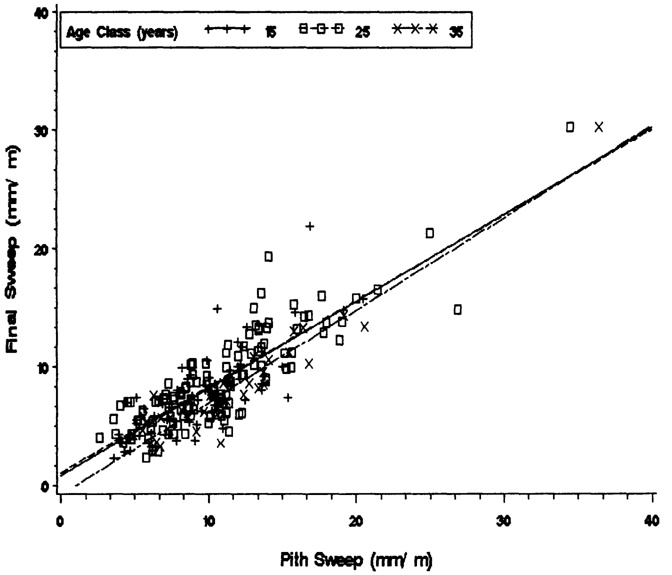

FIG. 5–Pith and final sweep data with linear regression trend lines fitted for three age-classes.

An analysis of variance (ANOVA) identified pith sweep, and age, as having a moderately significant (p=0.05) effect on final sweep. The effect of the pith sweep/age interaction on final sweep was not significant ($p > 0.05$), suggesting there are not separate regression slopes for different log ages. There are, however, separate regression intercepts for the different log ages. The model fitted had an r^2 of 0.78 and a RMSE of 2.04.

The inclusion of the variables discussed above—i.e., pith sweep, age, and diameter—in a stepwise regression identified two variables which provided significant ($p \leq 0.15$) explanation of the variation in final sweep: pith sweep and age. Prediction of final sweep from pith sweep and age is given by the model below (Eq. 2):

$$S_F = aS_P - b(AGE\text{-}28) \qquad r^2 = 0.77 \qquad \text{[Eq. 2]}$$

where: S_F is final sweep (mm/m)
S_P is pith sweep (mm/m)
AGE is time to harvest (years)
a, *b*, are regression coefficients.

Root mean square error (RMSE) for the model is 2.04.

In applying the relationship developed (Eq. 2), age was interpreted as the time in years to harvest. As pith sweep was used here to represent juvenile sweep, the average time to harvest for the study data set was equal to the age of the log when felled. *AGE-28* was used in the model to remove the need for an intercept term; *28* represented the average age of the logs used in the fitting of the model. The regression coefficient *a* represented the average percentage difference between pith and final sweep. For every one additional year to harvest, there was a decline in sweep of approximately 0.1 mm/m. Incorporating the effect of *AGE* into the regression model ensured that a swept tree measured for juvenile sweep at different ages gave similar estimates of final sweep. Having age in the model also allowed the assessment of effect of delaying harvest on final sweep.

To enable prediction of final sweep at all locations, the differences in the final sweep regression model (Eq. 2) among the study sites were explored. The plot of parameter estimates (Fig. 6) for Eq. 2, with their associated standard errors, showed the variation in parameters among the different locations.

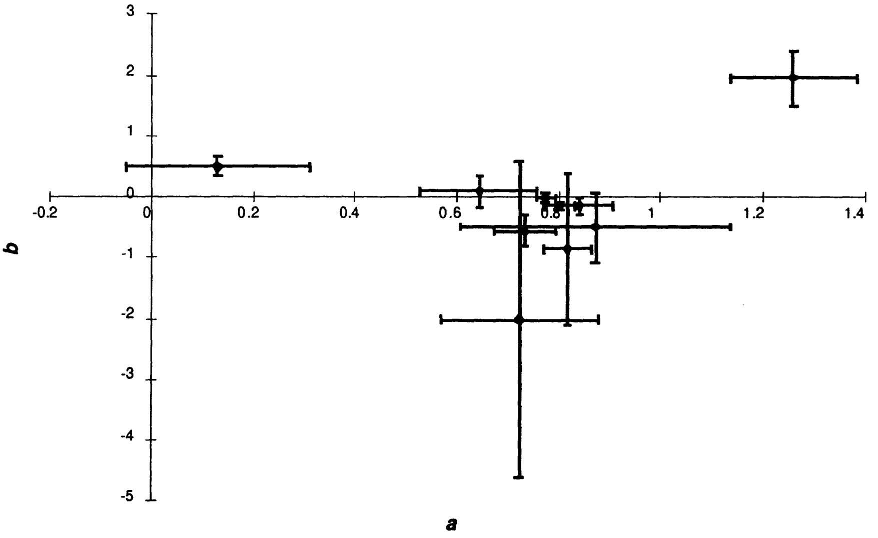

FIG. 6–Parameter estimates (*a* and *b*) and associated standard errors for the final sweep regression model (Eq. 2) fitted to log sweep data from individual study sites.

Locations appeared to differ in their estimates of both *a* and *b* coefficients, with two sites —Waiuku, with a low estimate of *a*, and Esk, with a high estimate of *a*—standing out in particular. Differences in parameter estimates among locations showed no relationship with site variables, site index, or selection ratio.

Although measurements of pith sinuosity have been used as an input (independent) variable in the development of these models, the input provided to STANDPAK is juvenile sinuosity measured after the final pruning lift. The age range of logs used to construct the revised sweep model was from 16 to 42 years. For this range of ages, the change of sweep with age was found to be constant, approximately 0.1 mm/m per year. Work by Maclaren (1995) and Cremer (1998) has demonstrated that sweep in *P. radiata* less than approximately 6 years old diminishes rapidly. This rapid change in sweep at young ages suggests assessments of final sweep from juvenile sweep measurements made on trees less than 6 years old will be over-estimated. In the few studies carried out in which measurements of juvenile sweep over successive years have been made (Schlesinger 1972; Maclaren 1995; Cremer 1998), no measurement was made of sweep at harvest. There are, therefore, no data currently available with which to develop models relating juvenile sweep to final sweep.

Prediction of Individual Log Sweep

Prediction of individual log mature sweep from stand average sweep is based on an exponential distribution of sweep. The apparently poor fit of the exponential distribution to the data used in this study (Fig. 7) suggested an alternative distribution may be required.

The comparison of chi-squared goodness-of-fit deviances for distributions fitted clearly shows the poor fit of the exponential distribution (Table 2). The lognormal, normal, and Weibull distributions appeared to provide good fits to the data at most of the locations. The lognormal was the best fit at six sites, and the normal was the best fit at five locations. The use of the lognormal distribution is preferred because it has consistently low deviances for all sites, and is an easier distribution to estimate than the Weibull.

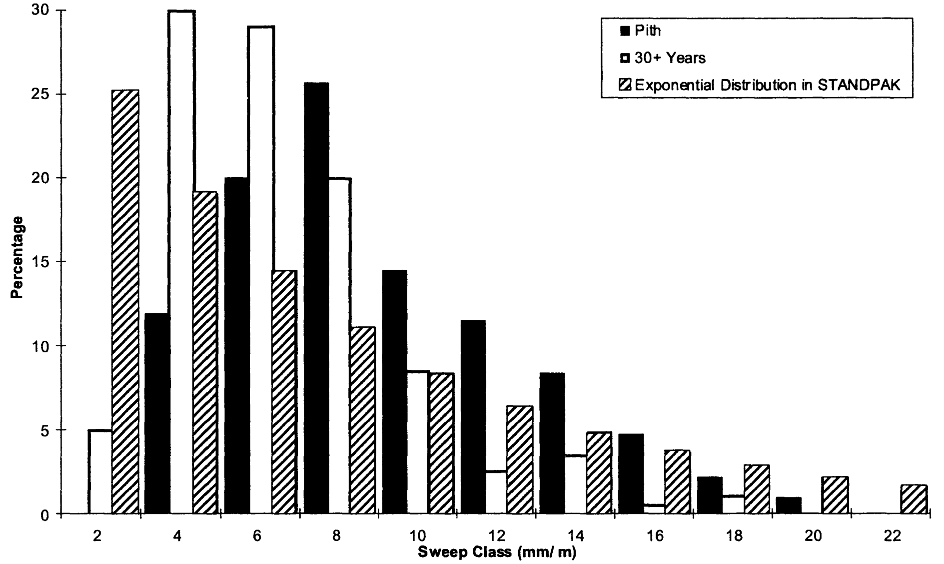

FIG. 7–Distribution of juvenile (pith) and final (age 30+ years) log sweep, with an exponential distribution fitted.

To enable prediction of individual log sweep at all locations, the differences in the lognormal distributions among the study sites were explored. The plot of parameter estimates (Fig. 8) for the lognormal distribution, with their associated standard errors, shows the variation in parameters among the different locations.

Locations differed significantly in their mean log sweep (μ), with logs from Waiuku having a particularly low level of mean sweep. Sites were similar in their estimated s; however, two sites, Waiuku and Rankleburn, had significantly lower estimates of s than the other sites. As the lognormal models fitted to most of the sites had similar estimated s, the

TABLE 2–Chi-squared goodness-of-fit deviances for exponential, lognormal, normal, and Weibull distributions derived for individual locations. The exponential distribution was fitted with 4 degrees of freedom (d.f.); all other distributions were fitted with 3 d.f. Deviances labelled with * identify data which are significantly different (α=0.10) from the fitted distribution.

Location	Count	Exponential	Normal	Weibull	Lognormal
Berwick	59	35.11*	6.97*	5.05	3.35
Esk	30	11.92*	7.46*	5.03	2.13
Golden Downs	43	28.68*	1.29	1.83	3.40
Gwavas	36	32.22*	8.98*	8.33*	5.47*
Kinleith	33	12.98*	0.78	0.87	3.48
Kaingaroa	78	53.05*	4.57	3.48	2.00
Mangatu	31	18.47*	1.69	1.74	2.31
Ngaumu	44	27.64*	12.88*	9.18*	3.13
Otago Coast	26	12.06*	0.44	0.22	1.00
Rankleburn	40	43.56*	1.49	2.18	1.99
Taupo	52	38.64*	6.00	5.37	5.59
Waiuku	25	23.02*	0.56	0.68	1.19
Waratah	33	21.73*	4.19	3.62	3.52
National	530	292.30*	29.7*	19.06*	4.10

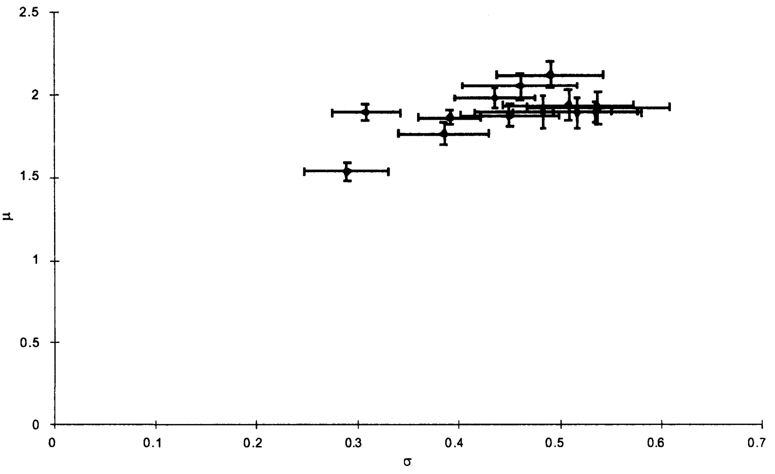

FIG. 8–Parameter estimates (μ and σ) and associated standard errors for the lognormal distributions fitted to log sweep data from individual study sites.

average s was used in the final model. The parameter μ for the lognormal distribution is related to the stand mean final sweep (S_F) by Eq. 3:

$$\mu = \ln(S_F) - \frac{\sigma^2}{2} \qquad \text{[Eq. 3]}$$

where: S_F is site mean final sweep (mm/m)
σ is the average estimated σ from the sites studied.

Proportions and means of logs in different sweep classes were therefore calculated using the lognormal distribution. The equation for calculating the percentage of logs between threshold levels l and k is described below as an example of the equation form (Eq. 4):

$$\%(\text{logs with sweep between } l \text{ and } k = \int_{\ln(l)}^{\ln(k)} \frac{1}{\sqrt{2\pi}\sigma} e^{-\left[\frac{(x-\mu)^2}{2\sigma^2}\right]} dx \qquad \text{[Eq. 4]}$$

where $x = \ln(S_F)$

$\mu = \ln(S_F) - \frac{\sigma^2}{2}$

l and k are threshold levels of sweep (mm/m).

The σ parameter for this distribution is an average of individual location estimate.

Validation of Prediction of Stand Mean Final Sweep

Measurements of pith sweep and age from "validation" data set logs were used in Eq. 2 to predict final sweep. The differences between actual and predicted final sweep (i.e., residuals) were then plotted against the predicted values and the variables in the model to examine for conditions under which error increased or bias was introduced. The errors in predicting final sweep for each of the "validation" log data set locations are shown in Fig. 9. The residual mean of 0.18 mm/m and standard error of the residual mean of 0.27 mm/m indicate a significant bias (p=0.01) in the residuals, with the regression model tending to under-predict final sweep. There are two logs for which the model appears to under-estimate final sweep with residuals greater than +5 mm/m (Fig. 9). These two logs are unusual in that they have a greater level of final sweep than pith sweep. When these two logs are removed from the "validation" data set the bias in the residuals is no longer strongly significant (p=0.05). There is an absence of any trend in the plot of residuals supporting the use of the untransformed variables (Fig. 9, 10, 11). Based on visual assessment of the graphs, the error in predicting final sweep using Eq. 2 can be expected to fall within ±5 mm/m.

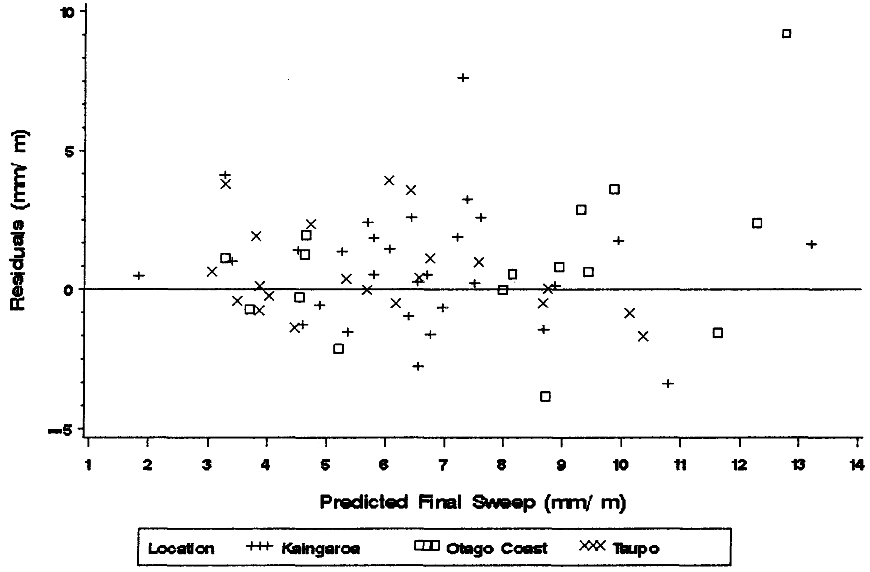

FIG. 9–Errors in predicted final sweep, by location, using Eq. 2.

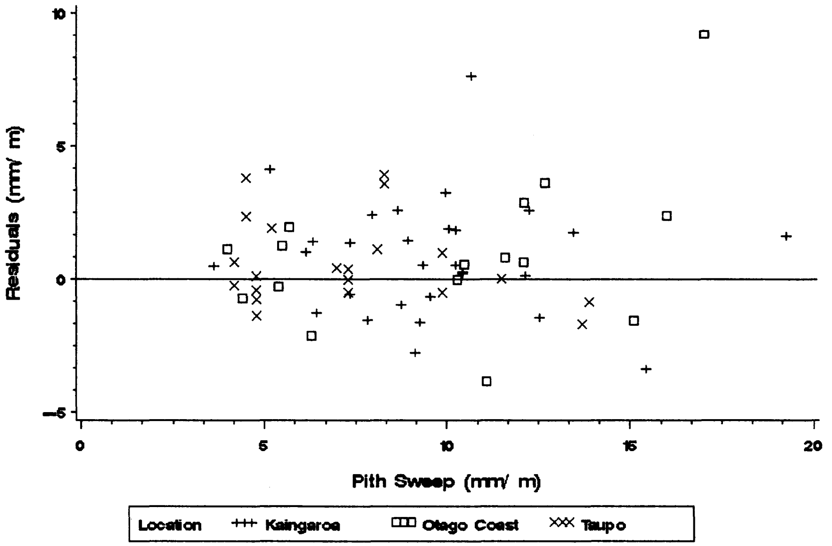

FIG. 10–Errors in predicted final sweep, by location, using Eq. 2 plotted against pith sweep.

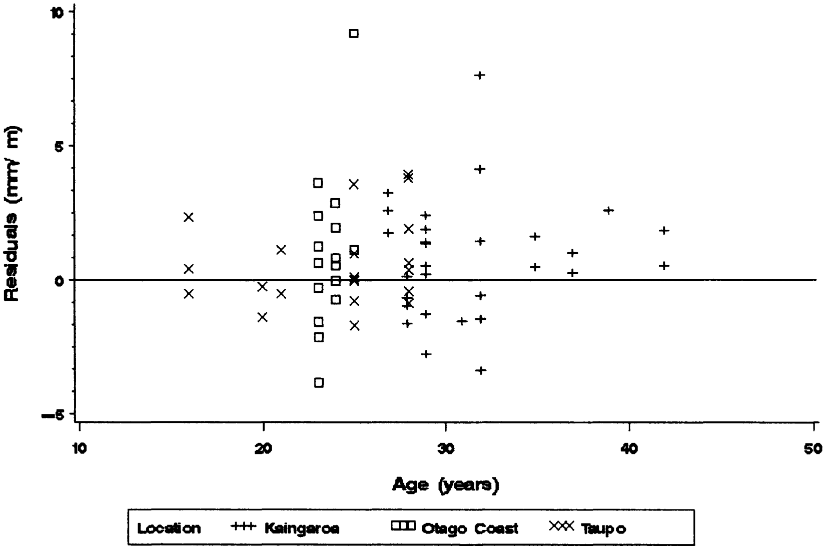

FIG. 11–Errors in predicted final sweep, by location, using Eq. 2 plotted against age (years).

Validation of Prediction of Individual Log Final Sweep

The plotting of residuals (actual frequency – predicted frequency) against final sweep classes (Fig. 12) identified biases in estimated proportions for the sweep classes. The lognormal distribution clearly tended to under-estimate percentage frequency for low levels of sweep, but there appeared to be little bias in the estimates of percentage frequency for

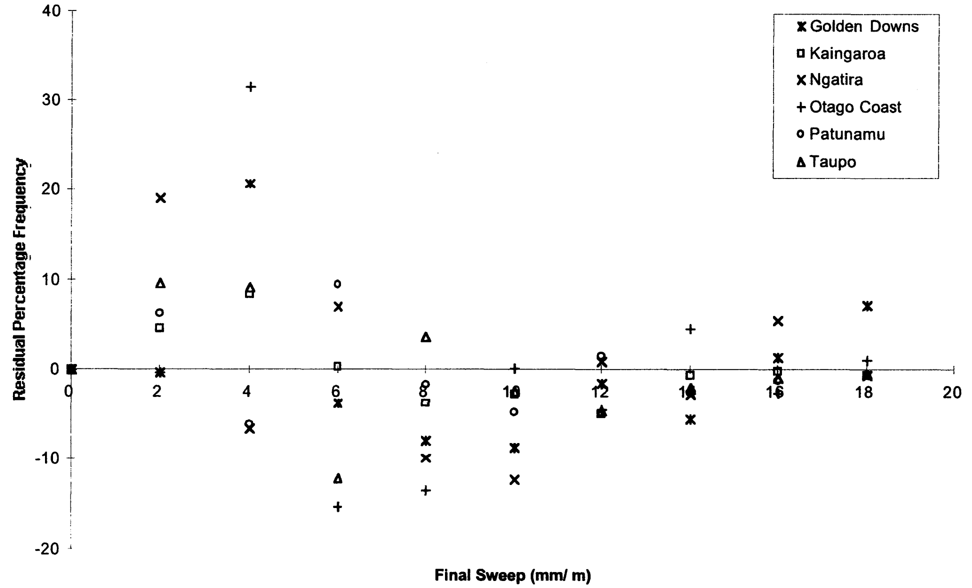

FIG. 12–Residual percentage frequency estimated using Eq. 7 against final sweep classes (mm/m).

higher levels of sweep. Based on this visual assessment of the plot (Fig. 12), the error in predicting percentage frequency of logs with final sweep in these log classes using Eq. 4 can be expected to fall within ±20%.

Application of the Sweep Model to Stand Management

Effect of age on stand mean sweep

In applying the relationship developed (Eq. 2), age is interpreted as the time in years to harvest. For every one additional year to harvest there is a decline in sweep of approximately 0.1 mm/m. Incorporating the effect of age into the regression model ensures that a swept tree measured for juvenile sweep at different ages will give similar estimates of final sweep. Having age in the model also allows the effect of delaying harvest on final sweep to be assessed.

Selection of final crop trees

Prediction of the proportion of logs in different sweep classes using the lognormal distribution enables prediction of final sweep for individual logs within a stand. The estimate of proportions of logs in different sweep classes can also be used in tree selection if it is interpreted as the probability of a tree with juvenile sweep X mm/m having final sweep in a particular sweep class. Threshold levels of juvenile sweep may therefore be set for pruning and thinning selection for a given time to harvest. For example, assuming 20 years to harvest, if a threshold level of sweep is 10 mm/m, a tree with juvenile sweep of 20 mm/m has a 9% chance of achieving a final sweep of 10 mm/m or less. A tree with juvenile sweep of 12 mm/m, on the other hand, has a 61% chance of achieving a final sweep of 10 mm/m or less.

CONCLUSION

Using key variables identified from a review of reports on stem straightness, a pith/final sweep model was fitted by stepwise regression,

$$S_M = aS_J - b(AGE\text{-}28) \text{ with } r^2=0.77$$

Validation of the regression model using residual analysis determined that the error in predicting final sweep with this equation could be expected to fall within ±5 mm/m. Prediction of proportions of logs with a certain level of sweep can be made using the lognormal distribution model identified by comparing chi-squared goodness-of-fit deviances for several distributions (Eq. 4). The σ parameter for this distribution is an average of individual location estimates. Based on the lognormal distribution fitted, the error in predicting percentage frequency of logs with final sweep in individual log classes can be expected to fall within ±20%.

An important limitation of this study is the use of pith sweep as a surrogate for juvenile sweep. Future work needs to involve yearly measurements of actual juvenile sweep and comparisons with final log sweep at varying ages.

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APPENDIX 1

SUMMARY STATISTICS FOR DATA SET USED TO FIT PITH/FINAL SWEEP RELATIONSHIP

Summary statistics for logs in the "sample" data set used to fit the pith/final sweep relationship.

Location	No. of logs	Mean (mm)		Minimum (mm)		Maximum (mm)	
		Pith	Final	Pith	Final	Pith	Final
Berwick	25	9.7	8.5	3.6	2.4	18.0	16.0
Esk	9	12.4	9.1	10.0	5.3	16.8	14.4
Woutu	5	20.6	15.8	14.1	10.3	36.5	30.3
Gwavas	13	8.6	6.7	5.5	3.3	13.2	13.5
Herbert	1	12.1	6.0	12.1	6.0	12.1	6.0
Kaingaroa	27	10.8	8.3	5.8	3.7	15.8	13.7
Kinleith	1	15.7	11.3	15.7	11.3	15.7	11.3
Mangatu	8	12.5	10.3	6.2	2.9	19.1	19.4
Mohaka	3	9.7	6.8	6.2	3.0	11.5	8.9
Ngaumu	14	14.8	11.8	7.4	5.8	34.5	30.3
Otago Coast	6	8.2	8.8	2.6	2.9	13.6	16.3
Rai Valley	2	11.8	7.5	11.2	7.2	12.4	7.7
Rankleburn	9	10.7	7.4	6.1	3.6	20.6	13.4
Taupo	28	10.3	8.9	4.2	3.7	18.9	13.3
Waiuku	6	7.6	5.5	4.9	4.3	10.6	6.4
Waratah	5	14.3	10.7	7.9	5.1	21.5	16.6

Summary statistics for the 162 logs in the "sample" data set used used to fit the pith/ final sweep relationship.

	Age (years)	dbh (cm)	Log length (m)
Mean	28	44.4	5.7
Minimum	16	23.2	3.1
Maximum	40	64.7	8.0

Summary statistics for logs in the "validation" data set used to fit the pith/final sweep relationship.

Location	No. of logs	Mean (mm/m)		Minimum (mm/m)		Maximum (mm/m)	
		Pith	Final	Pith	Final	Pith	Final
Kaingaroa	29	9.7	7.5	3.7	2.4	19.3	15.0
Otago Coast	16	10.0	8.8	4.0	3.0	17.0	22.0
Taupo	21	7.3	6.5	4.2	3.1	13.9	10.0

Summary statistics for the 66 logs in the "validation" data set used in this study.

	Age (years)	dbh (cm)	Log length (m)
Mean	27	44.1	5.7
Minimum	16	30.2	3.1
Maximum	42	64.2	8.0

APPENDIX 2

SUMMARY STATISTICS FOR DATA SET USED TO FIT DISTRIBUTIONS TO PREDICT INDIVIDUAL LOG SWEEP

Summary statistics for logs in the "sample" data set used to fit the distribution to predict individual log sweep.

Location	No. of logs	Mean (mm/m)	Minimum (mm/m)	Maximum (mm/m)
Berwick	59	8.0	2.4	16.6
Esk	30	7.9	1.8	14.4
Golden Downs	43	7.2	2.0	17.2
Gwavas	36	6.3	2.3	13.6
Kaingaroa	78	7.0	2.2	13.8
Kinleith	33	7.5	2.6	19.4
Mangatu	31	7.8	1.5	19.5
Ngaumu	44	9.5	2.6	30.3
Otago Coast	26	7.5	2.5	16.3
Rankleburn	40	7.0	3.6	13.5
Taupo	52	7.3	2.6	13.3
Waiuku	25	4.9	2.6	9.3
Waratah	33	8.7	2.3	17.1

Summary statistics for the 567 logs in the "sample" data set used used to fit the distribution to predict individual log sweep.

	Age (years)	dbh (cm)	Log length (m)
Mean	28	45.4	5.4
Minimum	16	23.2	2.0
Maximum	42	74.6	9.9

Summary statistics for logs in the "validation" data set used to fit the distribution to predict individual log sweep.

Location	No. of logs	Mean (mm/m)	Minimum (mm/m)	Maximum (mm/m)
Golden Downs	23	7.9	3.5	18.3
Kaingaroa	91	6.3	2.1	15.0
Ngatira	15	6.2	2.0	16.2
Otago Coast	42	7.6	3.0	22.0
Patunamu	14	6.1	1.2	11.4
Taupo	63	5.7	2.5	10.3

Summary statistics for the 248 logs in the "validation" data set used in this study.

	Age (years)	dbh (cm)	Log length (m)
Mean	27	44.7	5.5
Minimum	16	22.9	3.6
Maximum	42	70.0	7.0