PREDICTION OF FINAL STEM SINUOSITY IN PRUNED LOGS FROM JUVENILE STEM SINUOSITY MEASUREMENTS

J.A.TURNER & J.D. TOMBLESON

Report No. 45 May 1998

FOREST & FARM PLANTATION MANAGEMENT COOPERATIVE

EXECUTIVE SUMMARY

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The level of sweep in the pruned butt log, in conjunction with log diameter and length, affects the level of conversion to sawn timber, and hence, value of a log. To enable prediction of final crop value it is therefore useful to be able to accurately predict the degree of sweep in final pruned logs and relate this to the sweep present in the juvenile stand. 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 was used to improve the stand average and individual log sweep predictions made in the ***Forest Research*** stand modelling system STANDPAK. The pith/ final sweep model fitted using multiple regression techniques identified that on average the level of final sweep is 63.9% of the level of pith sweep. For every 1 cm of diameter increment there is a 0.5% reduction in the level of stem sinuosity, and for every 1 m reduction in log length there is a 3.5% reduction in stem sinuosity. 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. One limitation of this study is the potential bias in data due to logs measured in cross-cutting and sawing studies being selected as nominally straight. The bias resulted in a limited ability to identify clear differences in levels of sweep among study locations, therefore a national level model was developed. Another limitation is the uncertainty regarding the mechanism which results in swept trees having reduced sweep with increasing diameter. If differential radial growth is the mechanism, this has potential implications for the processing of logs which have had severe juvenile sweep. The final and most important limitation of this study is the use of pith sweep as a surrogate for juvenile sweep. This is likely to result in the model underestimating final sweep. Future work needs to be carried out in which measures of actual juvenile sweep are made and compared with final log sweep. It is intended that the model developed will be made available to Forest Farm Plantation Management Cooperative members in STANDPAK.

INTRODUCTION

Sweep in the pruned butt log has an important impact on the value of pruned logs (Cown *et al.* 1984; West & Kimberley 1991). The level of stem sinuosity in the pruned butt log, in conjunction with log diameter and length, affects the level of conversion of a log to sawn timber which in turn influences log value (MacDonald & Sutton 1970; Cown *et al.* 1984) (Figure 1).

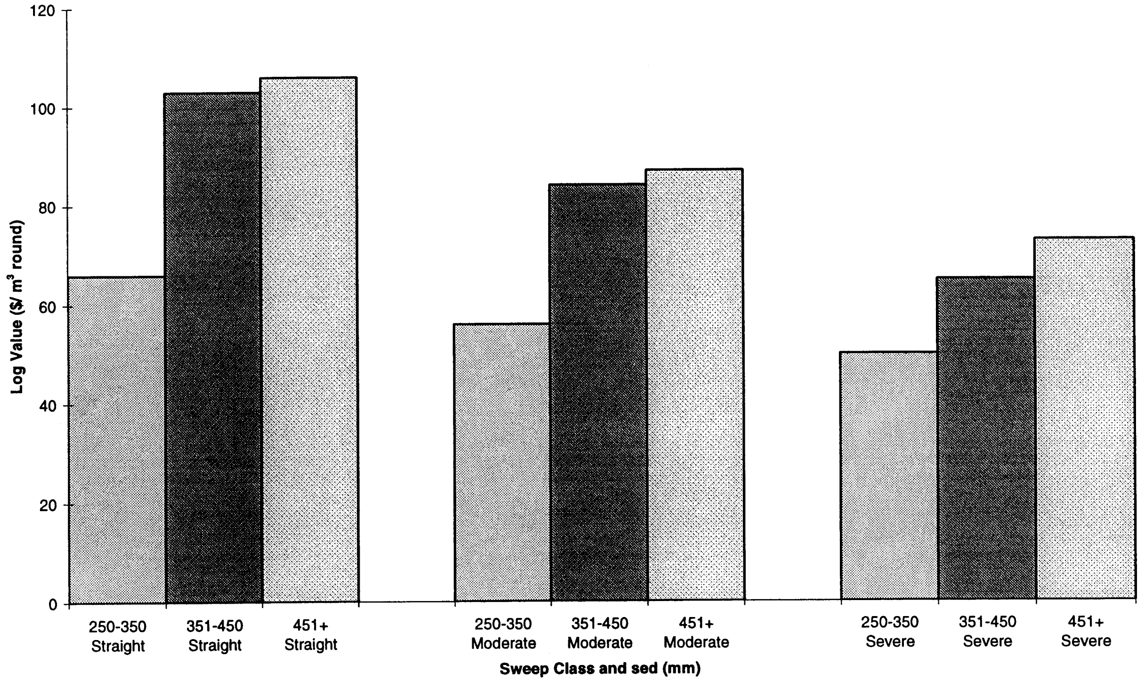

Figure 1: Effect of log size and sweep on pruned log value including a credit of \$12.5/ m^3 for sawmill residues. The sweep classes are straight < 10 mm/ m, moderate 11-20 mm/ m, and severe > 20 mm/ m. Source: Cown *et al.* 1984.

As well as reduced log value due to sweep, sawn timber defects which arise from stem sinuosity, such as sloping grain, compression wood, and pith defects, also reduce pruned log value (Fielding 1940; Nicholls 1982; Cown 1992). The accurate prediction of sweep in pruned logs at maturity is therefore important, if the value of a final crop is to be reliably determined. The ***Forest Research*** stand modelling system STANDPAK (Whiteside *et al.* 1989) can be used to predict individual pruned log sweep from measurements of sweep following final pruning. This provides an early indication of resource quality, and stand values. Knowledge of the relationship between juvenile sweep, and mature sweep, can also be used to guide tree selection criteria, for pruning and thinning.

Several factors appear to influence the level of sweep in the mature pruned log. The level of pith sinuosity should influence mature stem sinuosity as this pith sweep is what the tree must recover from. In this study pith sinuosity is used to represent the juvenile sweep that may be measured immediately following the final pruning lift. Stem diameter, as represented by small end diameter (sed), large end diameter (led), and diameter at breast height (dbh-stem diameter over bark at 1.4 m), potentially influences the level of mature sweep in terms of the amount of stem growth that has masked juvenile sinuosity. Whether this is an influence on the relationship between juvenile and stem sweep, is dependent on the mechanism by which trees improve stem form. The following three mechanisms are identified as likely explanations. The first, proposed by Jacobs (1938) suggests 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 and Wardrop (1949) is that stem form improvement is brought about by the development of reaction wood. Another mechanism is that improvement in stem form is the result of differential radial growth (Schlesinger 1972; Miller 1974) with greater stem growth on the inside of the stem sweep. The effect of age on the juvenile sweep/ mature sweep relationship is likely to be similar to that of log diameter, with an increase in age being associated with an increased log diameter (Schlesinger 1972; Miller 1974; Maclaren 1995). Increasing levels of sweep have been identified as being of increasing importance as the log length increases (MacDonald & Sutton 1970; Cown *et al.* 1984).

Prediction of mature sweep in STANDPAK is a two stage process; first 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 Mean Final Sweep

Juvenile sweep in the pruned butt log can be measured following final pruning using the measurement technique detailed by Maclaren (1992). STANDPAK presently uses these juvenile sweep measurements to predict stand average stem sinuosity at harvest using a linear relationship (Figure 2) between pith, as a surrogate for juvenile sweep, and final log sweep (Equation 1) developed using sweep measurements on 135 trees from six sites (Woods & Tombleson unpubl.; Pont 1994).

$$S_F = 0.6849S_P + 0.2185 \qquad R^2 = 0.55 \qquad \text{[Equation 1]}$$

where:
S_F is final sweep (mm/ m)
S_P is pith sweep (mm/ m).

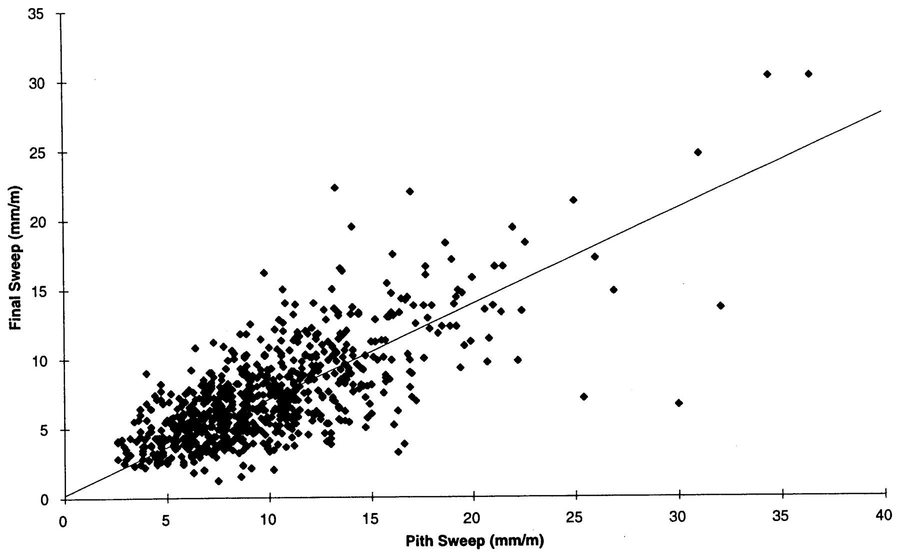

Figure 2: Present STANDPAK final sweep model (Woods & Tombleson unpubl.) fitted to the data set used in this study.

Individual Log Final Sweep

Individual log sweep within STANDPAK is estimated from the stand average stem sweep using an exponential distribution (Figure 3) (Gordon & Kimberley 1993). The proportion of logs and the mean sweep of those logs are then calculated based on the sweep limits defined in log grading rules (Gordon & Kimberley 1993).

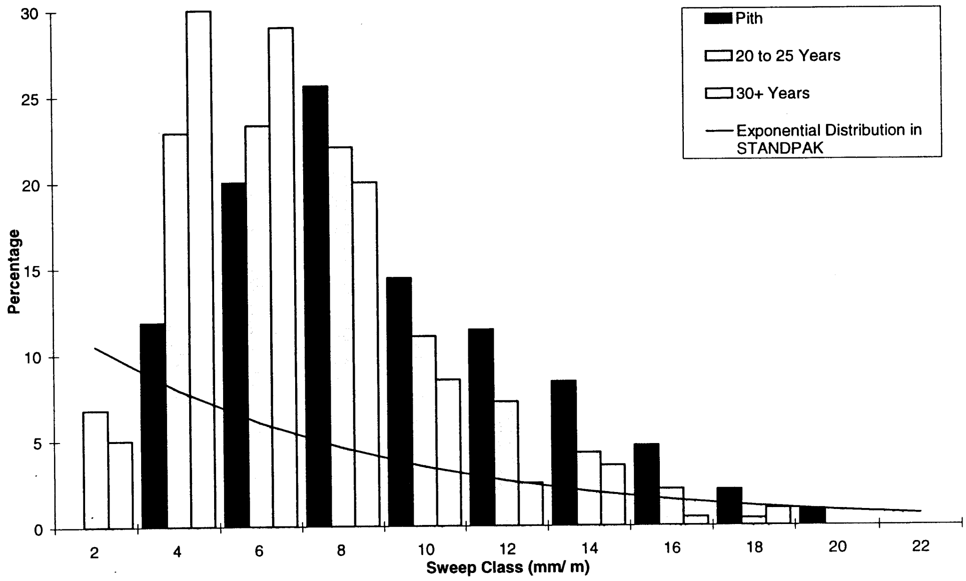

Figure 3: Distribution of juvenile (pith) and final (ages 30+ and 20 to 25 years) log sweep with an exponential distribution fitted to swept logs 30+ years old.

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

MATERIALS AND METHODS

Database

Data used in this study was derived from pruned log assessments made at 19 sites (Figure 4) using either of the following two assessment methods: sawing, which involves, measuring, sawing and then reassembling the log (Park 1987), or cross-sectional analysis, which involves, measuring, cross-cutting the log into discs, and recording the size and coordinates of all features affecting timber grade (Somerville 1985).

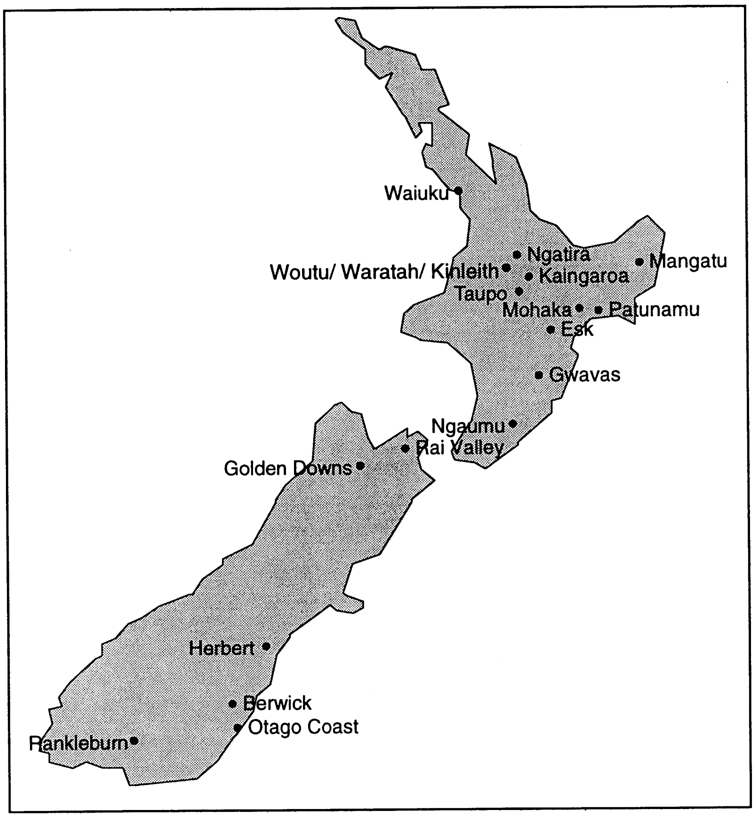

Figure 4: Location of stands for which pruned log assessments were made.

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. Logs selected also had to meet a minimum sed of 25 cm, and maximum stem deviation of 17 cm in order to be processed by the sawmill. Selection of logs for measurement by cross-sectional analysis (Somerville 1985) was based on the degree of stem sinuosity, 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 3). The selection of straight logs 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 Grallelis and Klomp (1982) identified a similar level of stem sinuosity in a Kaingaroa Spacing and Thinning trial as for the data used in this study (Table 3). Sweep ranged from 0 to 21 mm/ m, with an average sweep of 3 mm/ m for all trees, including nominally straight trees. Using the broad sweep classes devised by Cown *et al.* (1984) (Figure 1), 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).

Table 1: Percentage of logs by location occurring in each sweep class; straight (< 10 mm/ m), moderate (11 to 20 mm/ m), and severe (> 20 mm/ m).

	Percentage of Logs in Sweep Class		
Location	**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%	22.1%	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%

A comparison of the two data sources was made to determine if the method of log assessment might influence the fitting of a final sweep model. The plot of final sweep against pith sweep (Figure 5), with separate linear regression equations fitted to data from cross-sectional studies (Somerville 1985) and sawing studies (Park 1987) suggests data from the two sources differ in their final/ pith sweep relationship. An analysis of variance (ANOVA) confirms there are significant differences (p=0.01) in the final/ pith sweep relationship slope and intercept between methods of assessment.

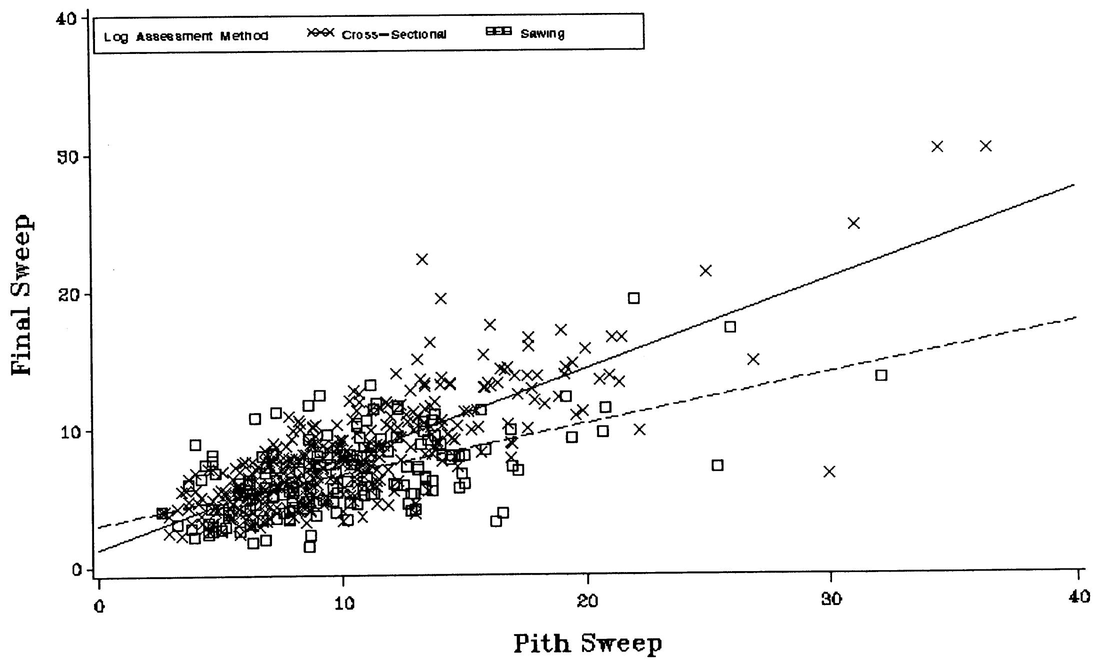

Figure 5: Separate trend lines fitted to log pith/ final sweep data from the cross-sectional (Somerville 1985) and sawing study (Park 1987) methods of log assessment.

The shallower slope of the trend-line fitted to the sawing study data shows this data to have less variation in final sweep compared with logs from cross-sectional analysis (Figure 5). This may be a reflection of a difference in average log size between the assessment methods and/ or the restriction on maximum stem deviation for the sawing study method. While logs measured using the sawing method are slightly larger in dbh, they are not significantly different ($p > 0.05$) in size compared with logs assessed by the cross-sectional method. Logs assessed by the sawing method have significantly ($p=0.01$) less stem deviation, independent of log length, compared with the cross-sectionally assessed logs (Table 2). As the difference in the final/ pith sweep relationship between the assessment methods appears to be due to differences in the selection criteria employed by the two methods, rather than selection of swept logs from separate populations, the data was pooled for further analysis.

Table 2: Mean, variance, minimum, and maximum final stem deviation independent of log length (mm) for cross-sectionally and sawing study assessed logs.

Method	Mean Deviation	Variance	Minimum	Maximum
Cross-sectional	44.0	517.6	13.4	195.1
Sawing	33.8	221.1	7.4	93.1

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

Pith sweep is measured in both the horizontal and vertical planes, assuming the log length extends in a longitudinal direction. In each plane, a line extending from the pith at either end of the log is constructed and the deviation of the measured pith points, from this line, calculated. Maximum pith sweep (mm/ m) is defined as the maximum deviation divided by the log length (Figure 6). Maximum final log sweep (mm/ m) is determined in a similar manner with lines constructed in two planes that join the centres of the log end cross-sections, which are assumed to be elliptical, and the deviation from the centre of each measured log cross-section ellipse calculated. Maximum log sweep is defined as the maximum deviation divided by the log length (Figure 6).

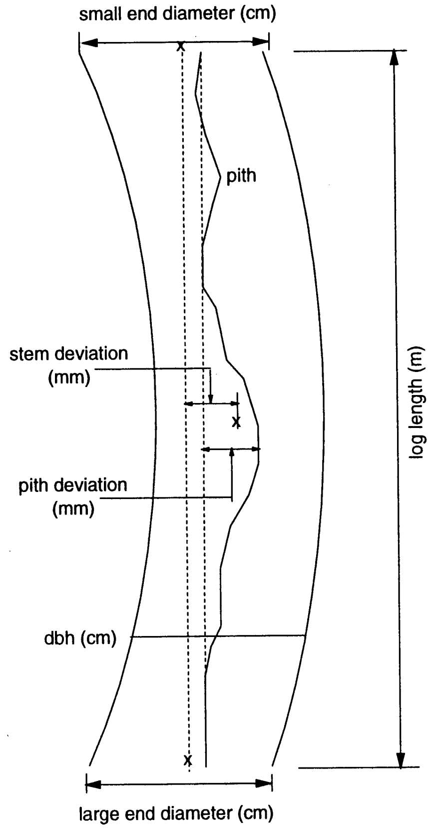

Figure 6: The centre to centre method of stem and pith sweep estimation.

At sites where there were a sufficient number of logs, the data was divided into "sample" sets (Tables 3 and 4) and "validation" sets (Tables 5 and 6) by randomly selecting approximately 50% of logs from each site. The data selected for the validation data set was not fully independent, in that logs from the same forest compartment formed the basis for 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.

Table 3: Summary statistics for logs in the "sample" data set. All sweep measurements are in mm/ m.

		Mean		Minimum		Maximum	
Location	No. of Logs	Pith	Final	Pith	Final	Pith	Final
Berwick	59	9.2	8.0	2.7	2.4	21.1	16.6
Esk	30	11.5	7.9	4.5	1.8	32.1	14.4
Woutu	8	20.5	15.3	12.7	7.9	36.5	30.3
Golden Downs	43	9.2	7.2	3.2	2.0	26.0	17.2
Gwavas	36	8.9	6.3	3.2	2.3	17.9	13.6
Herbert	14	9.9	5.5	3.7	2.6	16.3	8.7
Kaingaroa	78	9.3	7.0	2.9	2.2	18.3	13.8
Kinleith	33	11.6	7.5	3.8	2.6	25.4	19.4
Mangatu	31	9.8	7.8	2.6	1.5	19.1	19.5
Mohaka	5	10.0	6.8	6.2	3.0	14.1	10.2
Ngaumu	44	13.3	9.5	4.7	2.6	34.5	30.3
Otago Coast	26	8.0	7.5	2.6	2.5	14.6	16.3
Rai Valley	10	11.5	9.2	7.5	6.1	16.9	14.2
Rankleburn	40	9.8	7.0	2.6	3.6	20.6	13.5
Taupo	52	9.2	7.3	3.8	2.6	18.9	13.3
Waiuku	25	7.9	4.9	4.5	2.6	14.5	9.3
Waratah	33	12.0	8.7	4.0	2.3	21.5	17.1

Table 4: Summary statistics for the 567 logs in the "sample" data set used in this study.

	Age	DBH (cm)	Log Length (m)
Mean	28	45.4	5.4
Minimum	16	23.2	2.0
Maximum	42	74.6	9.9

Table 5: Summary statistics for logs in the "validation" data set. All sweep measurements are in mm/ m.

		Mean		Minimum		Maximum	
Location	No. of Logs	Pith	Final	Pith	Final	Pith	Final
Golden Downs	23	10.8	7.9	4.4	3.5	22.6	18.3
Kaingaroa	91	9.1	6.3	2.6	2.1	22.4	15.0
Ngatira	15	8.9	6.2	4.1	2.0	18.5	16.2
Otago Coast	42	8.5	7.6	2.8	3.0	17.0	22.0
Patunamu	14	8.0	6.1	5.4	1.2	12.4	11.4
Taupo	63	7.2	5.7	3.0	2.5	15.7	10.3

Table 6: Summary statistics for the 248 logs in the "validation" data set used in this study.

	Age	DBH (cm)	Log Length (m)
Mean	27	44.7	5.5
Minimum	16	22.9	3.6
Maximum	42	70.0	7.0

ANALYSIS

Stand Mean Final Sweep

The following variables were identified, from a review of literature, as potentially influencing the relationship between pith sinuosity and stem sinuosity; site, stand age, log diameter at breast height (dbh), log small and large end diameter (sed and led), and log length. The importance to enabling the prediction of stem sinuosity of all these variables, except for stand location, were tested using analyses of variance (ANOVAs) performed with PROC GLM in the SAS system (SAS Institute 1986), and stepwise linear regression. Stepwise regression 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). While stepwise regression produces a good model, that model is not necessarily the best. Four models modified from the stepwise regression results were therefore tested for prediction ability and goodness-of-fit using the PRESS statistic, root mean square error (RMSE), and coefficient of determination (R^2) derived from PROC REG output in SAS (SAS Institute 1986). The four models were also tested for their performance in predicting stem sinuosity at different locations, as separate location models and national models, by comparison of the RMSEs for each location. The final model selected 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 Prediction

Prediction of individual log mature sweep from stand average sweep is based on an exponential distribution of sweep (Equation 2). The apparently poor fit of the exponential distribution to the data used in this study (Figure 3) suggests an alternative distribution may be a more accurate fit. Several distributions; exponential (Equation 2), normal (Equation 3), lognormal (Equation 4), and Weibull (Equation 5), 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 is 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.

$$f(x;\mu)=\left(\frac{1}{\mu}\right)e^{-\frac{x}{\theta}}, \text{ for } x, \mu > 0 \qquad \text{[Equation 2]}$$

$$f(x;\mu,\sigma)=\frac{1}{\sqrt{2\pi\sigma}}e^{-\left(\frac{(x-\mu)^2}{2\sigma^2}\right)} \qquad \text{[Equation 3]}$$

$$f(log_e x;\mu,\sigma)=\frac{1}{\sqrt{2\pi\sigma}}e^{-\left(\frac{(log_e x-\mu)^2}{2\sigma^2}\right)} \qquad \text{[Equation 4]}$$

$$f(x;\alpha,\beta)=\frac{\alpha}{\beta^{\alpha}}x^{\alpha-1}e^{-(x/\beta)^{\alpha}} \qquad \text{[Equation 5]}$$

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 classes were 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 classes 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 classes may have less than 5 observations (logs), resulting in unreliable results from the chi-squared goodness-of-fit test (Bain & Engelhardt 1992). Setting the number of classes 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 (8 logs), Herbert Forest (14), Mohaka (5), and Rai Valley (10) were excluded from the data set for fitting distributions because the number of logs measured at these locations were 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 using 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

Several parameters were identified as potentially influencing the prediction of final stem sweep.

Pith Sinuosity

There appears to be a moderate linear relationship between final sweep and pith sweep (Figure 7) with an R^2 of 0.54 and a RMSE of 2.49. The large amount of variation in the data about the fitted trend line is likely to be a reflection of a considerable amount of pith sinuosity being kinks or wobble, rather than sweep.

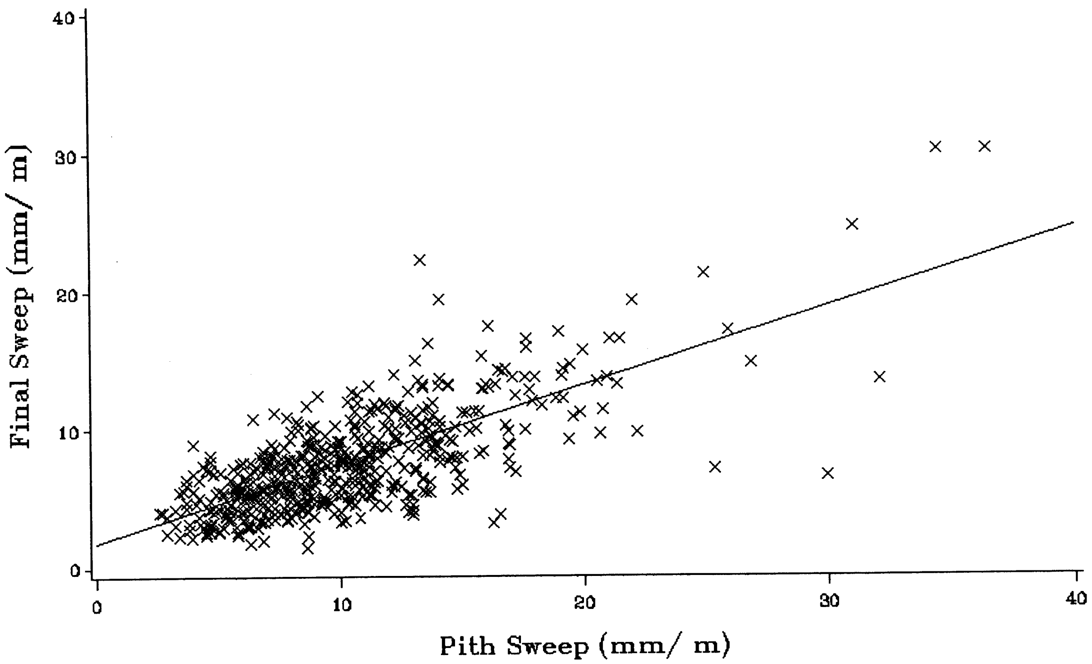

Figure 7: Final sweep plotted against pith sweep with a linear regression line fitted to the "sample" data set.

Two logs stand out as having unusually high levels of final sweep for their level of pith sweep (Figure 7). These logs appear to have a greater level of final sweep than pith sweep, possibly due to wind damage resulting in bending of the stem after the pith has been set.

Stem Diameter

A paired t-test performed on the deviation of the pith and the stem (mm), independent of log length for all logs in the data set identified a significant difference (p=0.01) in pith and stem deviation with the stem deviation being on average 75% that of pith deviation. This result indicates that improvement in stem form with increasing diameter is not simply due to sinuosity becoming a decreasing proportion of the stem with increasing stem diameter, as Jacobs (1938) suggests.

The plot of pith sweep against final sweep by dbh class shows a pattern of higher levels of final sweep, for a given level of pith sweep, with decreasing log diameter (Figure 8).

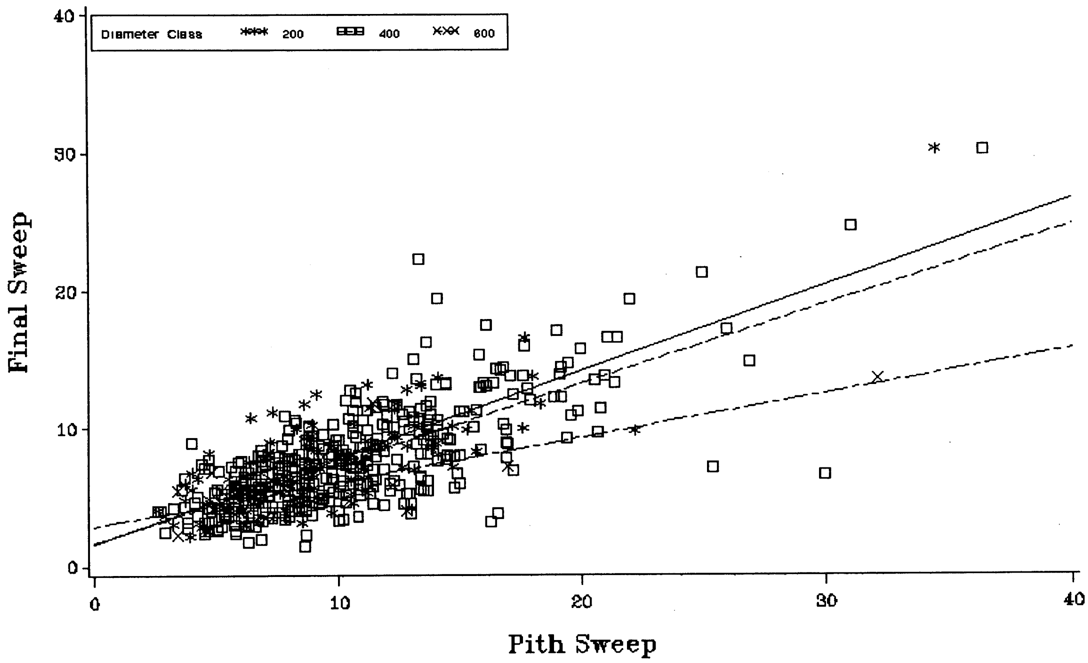

Figure 8: Pith and final sweep data with linear regression trend lines fitted for three diameter at breast height (dbh) classes.

An analysis of variance (ANOVA) exploring the effect of pith sweep and dbh on final sweep identifies pith sweep, dbh and their interaction as all having a significant (p=0.01) effect on final sweep (Table 7). The model fitted has an R^2 of 0.56 and a RMSE of 2.43.

Table 7: ANOVA of final sweep with effects due to pith sweep, dbh and pith sweep and dbh interaction terms for logs in the "sample" data set.

Source	DF	Mean Square	F Value	P > F
S_P	1	430.5	72.67	0.0001
DBH	1	40.8	6.89	0.0089
S_PDBH	1	111.1	18.76	0.0001
ERROR	563	5.9		

While the effect of dbh is significant, suggesting that there are separate regression intercepts for different levels of dbh, this effect is not as important as pith sweep and in reality zero pith sweep would be expected to be associated with zero final sweep regardless of log dbh.

Age

The plot of pith sweep against final sweep by age class shows a slight pattern of higher levels of final sweep, for a given level of pith sweep, with decreasing age (Figure 9).

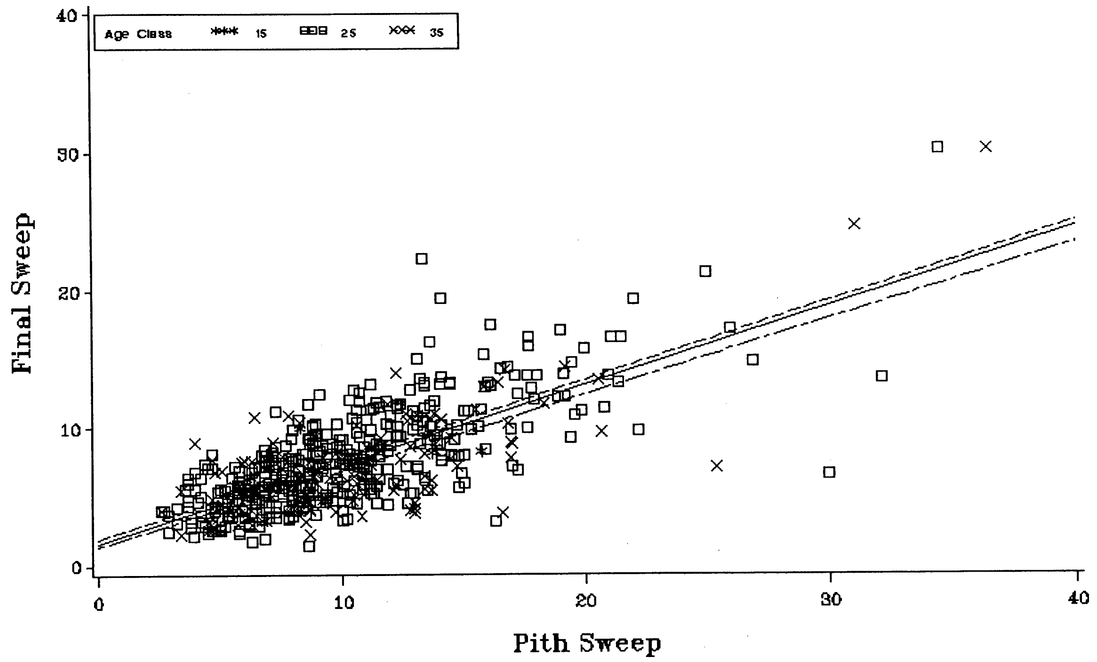

Figure 9: Pith and final sweep data with linear regression trend lines fitted for three age classes.

An analysis of variance (ANOVA) exploring the effect of pith sweep and age on final sweep identifies pith sweep, and the interaction term as having a significant (p=0.01) effect on final sweep (Table 8). The effect of age on final sweep is not significant ($p > 0.05$) suggesting there are not separate regression intercepts for different log ages. The model fitted has an R^2 of 0.56 and a RMSE of 2.45.

Table 8: ANOVA of final sweep with effects due to pith sweep, age, and pith sweep and age interaction terms for logs in the "sample" data set.

Source	DF	Mean Square	F Value	P > F
S_P	1	183.7	30.72	0.0001
AGE	1	0.8	0.13	0.7201
S_PAGE	1	27.6	4.62	0.0321
ERROR	563	6.0		

Log Length

The plot of pith sweep against final sweep by log length class shows a pattern of higher levels of final sweep, for a given level of pith sweep, with increasing log length (Figure 10).

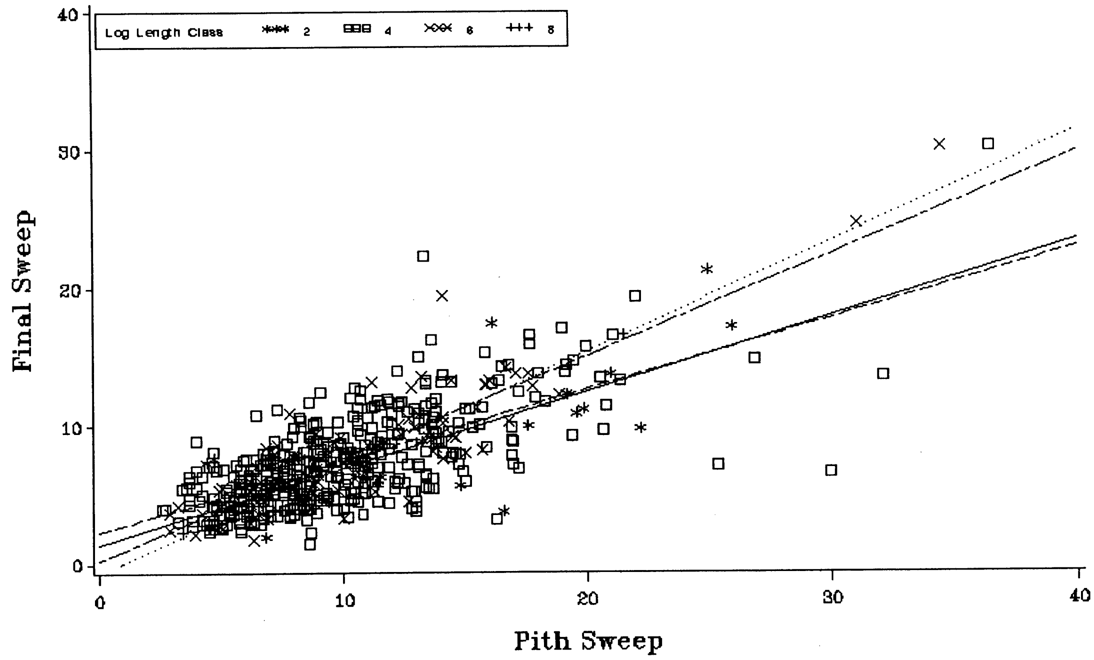

Figure 10: Pith and final sweep data with linear regression trend lines fitted for four log length classes.

An analysis of variance (ANOVA) exploring the effect of pith sweep and log length on final sweep identifies log length, and the interaction term as having a significant (p=0.01) effect on final sweep (Table 9). The effect of pith sweep on final sweep is not significant ($p > 0.05$). The model fitted has an R^2 of 0.56 and a RMSE of 2.44.

Table 9: ANOVA of final sweep with effects due to pith sweep, log length and pith sweep and log length interaction terms for logs in the sample data set.

Source	DF	Mean Square	F Value	P > F
S_P	1	11.6	1.94	0.1640
LT	1	35.9	6.02	0.0145
S_PLT	1	103.7	17.40	0.0001
ERROR	563	6.0		

While the effect of log length is significant, suggesting that there are separate regression intercepts for different log lengths in reality zero pith sweep would be expected to be associated with zero final sweep regardless of log length. While it would be expected that the effect of log length on the juvenile/ mature sweep relationship would be curvilinear, however the large amount of variation in the data precluded reliable analysis of this effect.

The inclusion of the variables discussed above, in a stepwise regression (Table 10) identified seven variables which appeared to provide significant ($p \leq 0.15$) explanation of the variation in final sweep; pith sweep, pith sweep/ age interaction, pith sweep/ log length interaction, pith sweep/ dbh interaction, sed, pith sweep/ led interaction and log length.

Table 10: Summary statistics from the stepwise regression for final sweep. S_P is pith sweep (mm/ m), *AGE* is log age (years), *DBH* is diameter at breast height (cm), *SED* is small end diameter (cm), *LED* is large end diameter, and *LT* is log length (m).

Variable Entered	Model R^2	F value	Prob>F
S_P	0.54	662.2	0.0001
S_PAGE	0.56	20.9	0.0001
S_PLT	0.57	17.9	0.0001
S_PDBH	0.58	10.4	0.0013
SED	0.59	15.0	0.0001
S_PLED	0.59	3.8	0.0531
LT	0.59	2.8	0.0977

The further selection of appropriate variables for inclusion in the final model is based on identifying the combination of variables which relate to variables identified in the literature review as influencing the reduction in stem sinuosity. SED, S_PAGE, S_PDBH and S_PLED are highly positively correlated, and relate to the same mechanism leading to the reduction of stem sinuosity, ie., differential radial growth (Schlesinger 1972; Miller 1974), therefore it would be unnecessary to include all four effects in the final model of final sweep.

Small end diameter may be expected to be a stronger influence on final sweep than large end diameter as it is not influenced by butt flare and incorporates an effect of log length by becoming smaller with increasing log length, therefore perhaps being of use for second log pruning. Log length was identified as a significant influence on the reduction of stem sinuosity, however, this influence is slightly nonsensical as it would suggest that for zero pith sweep the level of final sweep may differ depending on log length. Both dbh and age may be interacting to influence the relationship between final and pith sweep. The high correlation between age and dbh (R=0.91) for logs in the study data set, however precluded exploration of this interaction. Investigation of four models was made, all including pith sweep and pith sweep/ log length interaction effects, differing only in the inclusion of a led, age and dbh interaction with pith sweep, and sed.

Prediction of final sweep from pith sweep, pith sweep/ large end diameter interaction, pith sweep/ log length interaction is given by the model below (Equation 6):

$$S_F = 0.574S_P - 0.003S_PLED + 0.037S_PLT + 1.543 \quad R^2 = 0.56 \quad \text{[Equation 6]}$$

where: S_F is final sweep (mm/ m)
S_P is pith sweep (mm/ m).
LED is large end diameter (cm)
LT is log length (m).

Root mean square error (RMSE) for the model is 2.43 and the PRESS statistic is 2.1927×10^{20}.

Table 11: Equation 6 parameter estimates and standard errors of parameter estimates.

Variable	Parameter Estimate	Standard Error
S_P	0.574	0.085
S_PLED	-0.003	0.001
S_PLT	0.037	0.010
Intercept	1.543	0.247

Prediction of final sweep from pith sweep, pith sweep/ age interaction, pith sweep/ log length interaction is given by the model below (Equation 7):

$$S_F = 0.674S_P - 0.011S_PAGE + 0.040S_PLT + 1.609 \quad R^2 = 0.57 \quad \text{[Equation 7]}$$

where: S_F is final sweep (mm/ m)

S_P is pith sweep (mm/ m).

AGE is log age (years)

LT is log length (m).

Root mean square error (RMSE) for the model is 2.41 and the PRESS statistic is 4.1207×10^{19}.

Table 12: Equation 7 parameter estimates and standard errors of parameter estimates.

Variable	Parameter Estimate	Standard Error
S_P	0.674	0.083
S_PAGE	-0.011	0.002
S_PLT	0.040	0.010
Intercept	1.609	0.242

Prediction of final sweep from pith sweep, small end diameter, pith sweep/ log length interaction is given by the model below (Equation 8):

$$S_F = 0.391S_P - 0.029SED + 0.036S_PLT + 2.814 \quad R^2 = 0.56 \quad \text{[Equation 8]}$$

where: S_F is final sweep (mm/ m)

S_P is pith sweep (mm/ m).

SED is log small end diameter (cm)

LT is log length (m).

The root mean square error (RMSE) for the model is 2.45 and the PRESS statistic is 1.055×10^{20}.

Table 13: Equation 8 parameter estimates and standard errors of parameter estimates.

Variable	Parameter Estimate	Standard Error
S_P	0.391	0.054
SED	-0.029	0.015
S_PLT	0.036	0.010
Intercept	2.814	0.650

The coefficient for the SED variable was not significant ($p>0.05$) suggesting that small end diameter failed to explain a significant proportion of the variation in final sweep.

Prediction of final sweep from pith sweep, pith sweep/ dbh interaction, pith sweep/ log length interaction is given by the model below (Equation 9):

$$S_F = 0.639S_P - 0.005S_PDBH + 0.035S_PLT + 1.538 \quad R^2 = 0.57 \quad \text{[Equation 9]}$$

where: S_F is final sweep (mm/ m)

S_P is pith sweep (mm/ m).

DBH is diameter at breast height (cm)

LT is log length (m).

The root mean square error (RMSE) for the model is 2.42 and the PRESS statistic is 3.3415×10^{20}.

Table 14: Equation 9 parameter estimates and standard errors of parameter estimates.

Variable	Parameter Estimate	Standard Error
S_P	0.639	0.085
S_PDBH	-0.005	0.001
S_PLT	0.035	0.010
Intercept	1.538	0.245

The parameter estimates of the model (Table 14) provide information on the relative effect of diameter increment and changes in log length on the level of stem sinuosity. On average the level of final sweep is 63.9% of the level of pith sweep. For every 1 cm of diameter increment there is a 0.5% reduction in the level of stem sinuosity (Figure 8), and for every 1 m reduction in log length there is a 3.5% reduction in stem sinuosity (Figure 10).

None of the four models appear to be better or worse predictors of the variation among locations, as shown by the comparable RMSEs for the four models fitted to individual location data (Table 15), therefore the model incorporating dbh (Equation 8) was selected as being most suitable.

Table 15: Root mean square errors (RMSE) by location for final sweep models containing dbh, large end diameter and age variables fitted to individual location data and national data.

	Individual Location				National			
Location	Diameter	LED	SED	Age	Diameter	LED	SED	Age
Berwick	1.96	1.94	1.97	1.94	2.24	2.25	2.29	2.15
Esk	2.43	2.26	2.46	2.32	2.59	2.60	2.73	2.81
Woutu	2.68	1.65	2.21	2.43	5.21	5.15	5.32	6.04
Golden Downs	2.20	2.22	2.17	2.12	2.25	2.29	2.29	2.26
Gwavas	1.93	1.90	1.94	1.93	2.03	2.01	2.07	2.04
Herbert	1.66	1.80	1.73	1.72	3.98	3.97	3.96	4.20
Kaingaroa	1.72	1.73	1.76	1.76	1.79	1.79	1.81	1.80
Kinleith	2.92	2.84	2.94	2.70	3.51	3.56	3.60	3.36
Mangatu	2.69	2.68	2.69	2.61	2.82	2.79	2.81	2.88
Mohaka	0.95	-[1]	0.24	0.68	-[1]	-[1]	-[1]	-[1]
Ngaumu	3.86	3.92	3.89	3.68	4.01	4.07	4.06	4.00
Otago Coast	2.01	2.11	2.18	2.23	2.99	3.02	3.02	2.82
Rai Valley	2.42	2.56	2.49	2.57	3.59	3.54	3.50	3.61
Rankleburn	1.66	1.58	1.71	1.73	2.25	2.22	2.22	2.17
Taupo	1.78	1.76	1.79	1.77	1.83	1.83	1.83	1.95
Waiuku	1.31	1.22	1.30	1.30	2.52	2.56	2.51	1.83
Waratah	2.42	2.39	2.40	2.42	2.58	2.59	2.51	2.51

The addition of a variable for location in the models showed a significant difference ($p = 0.01$) in the pith/ final sweep relationship among locations. The impracticality of having separate models for each location led to the exploration of variables which may explain the differences among locations. Variables tested were dbh, average annual diameter increment, site index and a diameter/ age interaction variable. None of these variables were significant in the ANOVA ($p > 0.05$) except for average annual diameter increment, therefore while the combined site model is a poorer predictor than the individual location models because of the impracticality of using individual location models, the national model was used.

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 following the final pruning lift. Measurements of juvenile sweep and final sweep have not been made precluding the development of such models. The model developed here, however, may be considered a good approximation, although it is likely to slightly under-predict mature sweep as the pith sweep is greater than that which would be measured following the final pruning lift to a height of 6 m at tree age 6 to 8 years.

[1] A root mean square error could not be calculated due to the model degrees of freedom equalling the number of logs measured at this location.

Prediction of Individual Log Sweep

The comparison of chi-squared goodness-of-fit deviances for distributions fitted clearly show the poor fit of the exponential distribution (Table 16). The lognormal, normal, and Weibull distributions appear to provide good fits to the data at most of the locations. The lognormal is the best fit at six sites, while the normal is 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.

Table 16: 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 labeled with a * identify data which is 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

To enable prediction of individual log sweep at all locations the differences in the lognormal distributions among the study sites was explored. The plot of parameter estimates (Figure 11) for the lognormal distribution, with their associated standard errors shows the variation in parameters among the different locations.

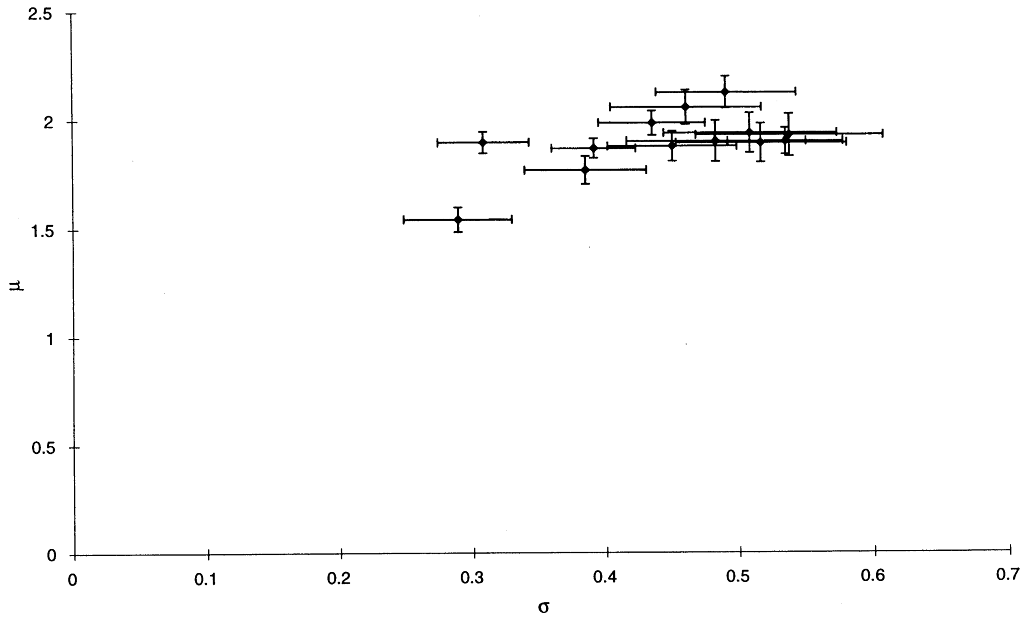

Figure 11: Parameter estimates (μ and σ) and associated standard errors for the lognormal distributions fitted to log sweep data from individual study sites.

Locations significantly differ in their mean log sweep (μ) (Table 17), with Waiuku having a particularly low level of mean sweep. Sites are similar in their estimated σ (Table 18), however two sites, Waiuku, and Rankleburn, have significantly lower estimates of σ compared with the other sites.

Table 17: Estimated μ and associated standard errors for lognormal distributions fitted to each study site. The final column of the table indicates those locations that have significantly different μ based on the LSD test. Seedlots followed by the same letter do not differ significantly ($p>0.05$).

Location	μ	Standard Error	
Ngaumu	2.13	0.0741	a
Waratah	2.06	0.0803	ab
Berwick	1.99	0.0567	abc
Mangatu	1.94	0.0914	abcd
Esk	1.93	0.0983	abcd
Otago Coast	1.90	0.0948	abcd
Taupo	1.90	0.0604	bcd
Rankleburn	1.90	0.0488	bcd
Kinleith	1.89	0.0901	bcd
Golden Downs	1.88	0.0688	bcd
Kaingaroa	1.87	0.0444	cd
Gwavas	1.77	0.0643	d
Waiuku	1.54	0.0578	e

Table 18: Estimated σ and associated standard errors for lognormal distributions fitted to each study site.

Location	σ	Standard Error	
Esk	0.54	0.0696	ab
Taupo	0.54	0.0427	a
Kinleith	0.52	0.0637	ab
Mangatu	0.51	0.0647	ab
Ngaumu	0.49	0.0524	ab
Otago Coast	0.48	0.0671	ab
Waratah	0.46	0.0568	ab
Golden Downs	0.45	0.0486	ab
Berwick	0.44	0.0401	ab
Kaingaroa	0.39	0.0314	bc
Gwavas	0.39	0.0454	bc
Rankleburn	0.31	0.0345	c
Waiuku	0.29	0.0409	c

As the lognormal models fitted to most of the sites have similar estimated σ, the average σ was used in the final model. The natural log of mean sweep is not equal to the mean of the natural log of sweep a linear relationship between the parameter μ and site mean sweep was therefore calculated using simple linear regression. The relationship developed (Equation 10) is of the form:

$$\mu = 0.1235S_F + 0.9824 \qquad R^2 = 0.97 \qquad \text{[Equation 10]}$$

where: S_M is site mean final sweep (mm/ m). The root mean square error (RMSE) for the model is 0.0267.

Proportions and means of logs in different sweep classes are therefore calculated using the lognormal distribution (Equation 11):

$$f(x;\mu,\sigma)=\frac{1}{\sqrt{2\pi}\sigma}e^{-\left(\frac{(x-\mu)^2}{2\sigma^2}\right)} \qquad \text{[Equation 11]}$$

where $x = \log_e(x)$

$\mu = 0.1235S_F + 0.9824$

$\sigma = 0.4459$.

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

If a representative log has a mean sweep s, and sweep class limits are s_1 and s_2 the proportion of logs greater than the sweep limits calculated using Equation 10 are y_1 and y_2 respectively. The proportion of logs < s_1 = 1 - y_1; the proportion of logs between s_1 and s_2 = y_1 - y_2; and the proportion of logs > s_2 = y_2. For each of these calculated proportions the mean sweep is calculated using the following formulae (Gordon & Kimberley 1993):

the mean sweep of logs < s_1 = $\dfrac{s - y_1(s_1 + s)}{1 - y_1}$;

the mean sweep of logs between s_1 and s_2 = $\dfrac{y_1(s_1 + s) - y_2(s_2 + s)}{y_1 - y_2}$;

and the mean sweep of logs > s_2 = $s\left(\dfrac{s_2}{s} + 1\right) = s_2 + s$

VALIDATION

Prediction of Stand Mean Final Sweep

Measurements of pith sweep, dbh and log length from ‘validation’ data set logs were used in Equation 9 to predict final sweep. The differences between actual and predicted final sweep (ie., 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. Figure 12 shows the errors in predicting final sweep for each of the ‘validation’ log data set locations. Figures 13 to 15 indicate no bias in estimates of final sweep for the levels of pith sweep, dbh and log length for logs in the ‘validation’ data set. No trend in the plot of residuals supports the use of the untransformed variables. There are two logs, for which the model appears to underestimate final sweep with residuals greater than +10 mm/ m (Figures 12 to 15). These two logs are unusual in that they have a greater level of final sweep than pith sweep. Based on the graphs, the error in predicting final sweep using Equation 9 can be expected to fall within ±12 mm/ m. The large amount of variation in the data about the fitted model is likely to be a reflection of a considerable amount of pith sinuosity being kinks or wobble, rather than sweep.

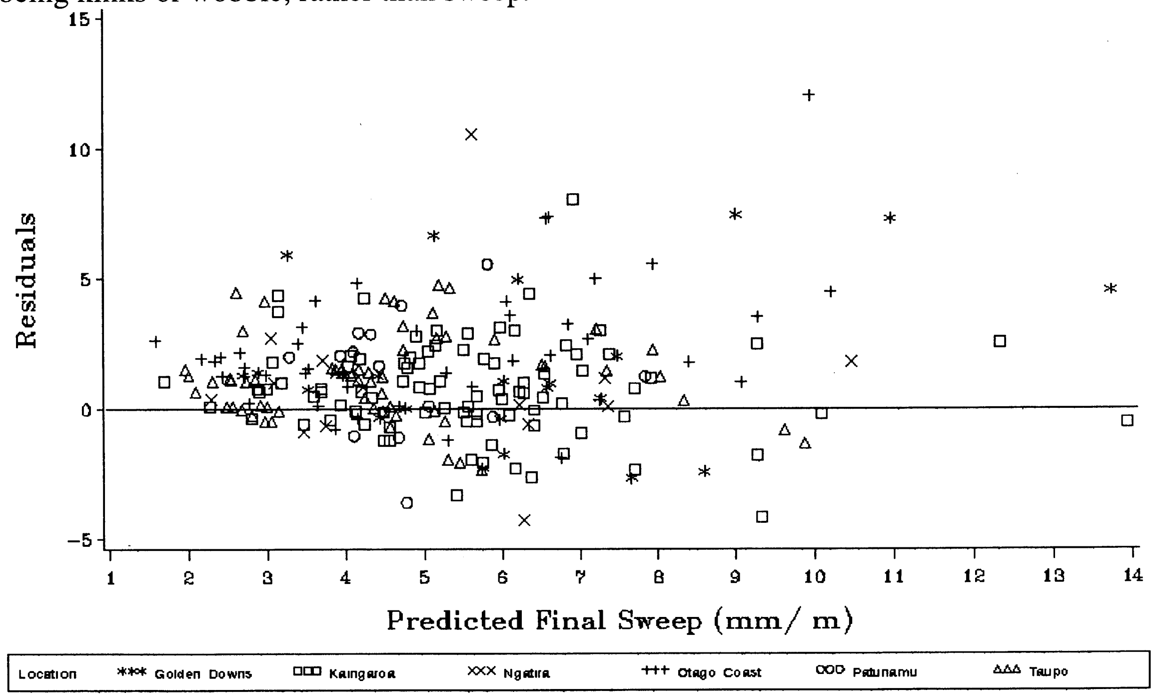

Figure 12: Errors in predicted stem sinuosity, by location, using Equation 9.

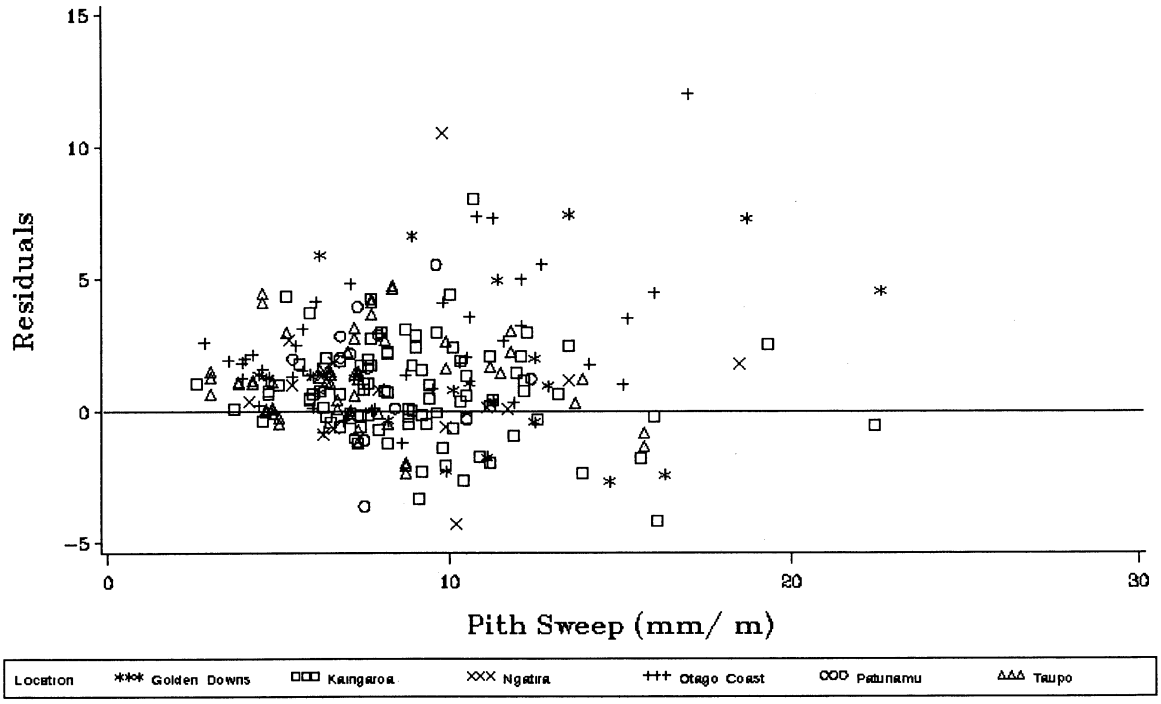

Figure 13: Errors in predicted stem sinuosity, by location, using Equation 9 plotted against pith sinuosity.

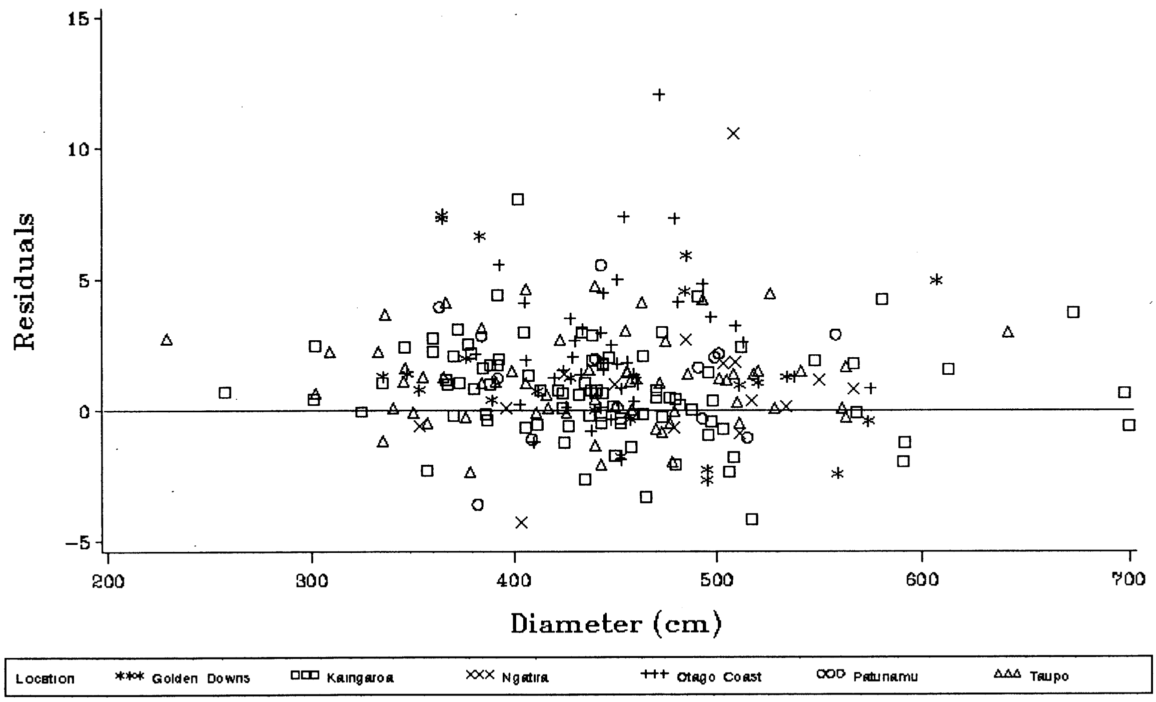

Figure 14: Errors in predicted stem sinuosity, by location, using Equation 9 plotted against diameter at breast height (dbh).

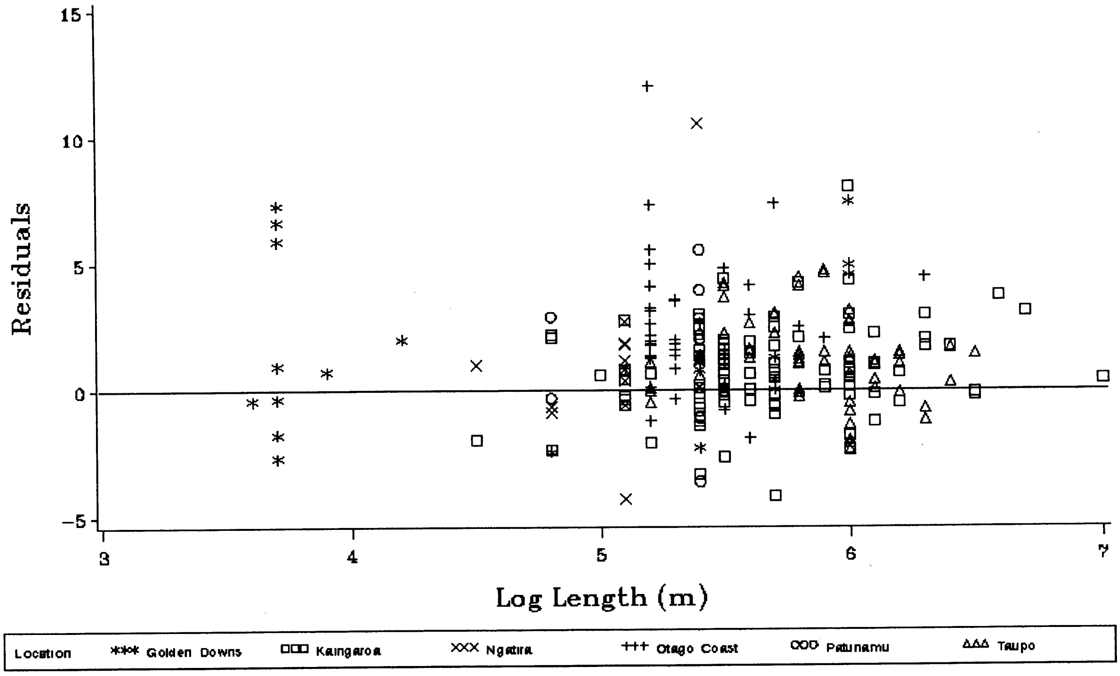

Figure 15: Errors in predicted stem sinuosity, by location, using Equation 9 plotted against log length.

The model was also checked across a range of dbh, log length and pith sweep to identify limits outside of which sensible estimates of final sweep could not be made. The model provides reliable estimates of final sweep for all levels of pith sweep within the range of the data used. Estimates of final sweep are greater than pith sweep for log lengths of more than 10 m, in combination with dbh less than 12 cm. Within these limits and within the range of the variables in the study data set the model appears to give realistic estimates of final sweep.

Prediction of Individual Log Final Sweep

The plotting of residuals (actual frequency - predicted frequency) against final sweep classes (Figure 16) identifies biases in estimated proportions for the sweep classes. The lognormal distribution clearly tends to underestimate percentage frequency for low levels of sweep. There appears to be little bias in the estimates of percentage frequency for higher levels of sweep. Based on this evidence (Figure 16), the error in predicting percentage frequency of logs with final sweep in these log classes using Equation 10 can be expected to fall within ±20%.

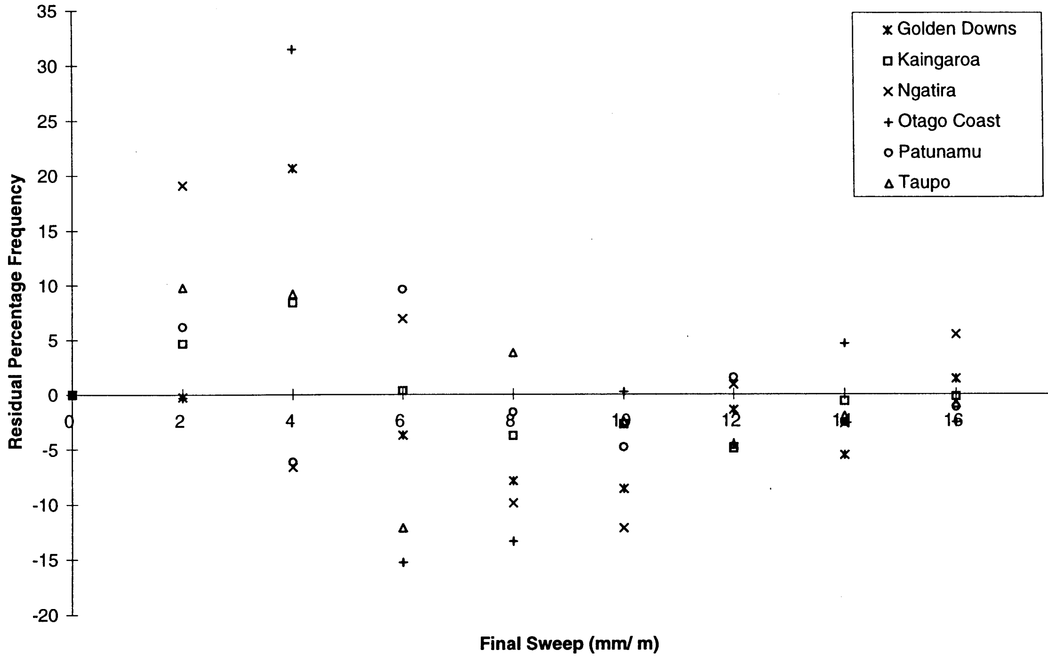

Figure 16: Residual percentage frequency estimated using Equation 11 against final sweep classes (mm/ m).

CONCLUSION

Using key variables identified from a review of stem straightness literature a pith/ final sweep model was fitted by stepwise regression, $S_M = 0.639S_J - 0.005S_JDBH + 0.035S_JLT + 1.538$ with R^2 0.57. Validation using residual analysis determined that the error in predicting final sweep using this equation can be expected to fall within ±12 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.

$$f(x;\mu,\sigma)=\frac{1}{\sqrt{2\pi}\sigma}e^{-\left(\frac{(x-\mu)^2}{2\sigma^2}\right)}$$

where $x = \log_e(x)$

$\mu = 0.1235S_M + 0.9824$

$\sigma = 0.4459$.

The σ parameter for this distribution is an average of individual location estimates. The μ parameter is estimated for an individual location using the relationship, $\mu = 0.1235S_M + 0.9824$ with R^2 0.97. 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%.

There are several important limitations with the data and methods used in this study which must be considered when applying the models developed. The logs measured from both cross-cutting and sawing studies were selected as nominally straight, therefore the data used to develop the models here covers a limited range of sweep. The bias in the data used has also resulted in a limited ability to identify clear differences in levels of sweep among study locations, therefore a national level model was developed due to the inability to account for any regional differences in pith/ final sweep relationship. The use of pith sweep as a surrogate for juvenile sweep due to lack of measurements of juvenile and final sweep on logs is likely to result in the model developed, in general, underestimating final sweep. A final limitation of this study is the uncertainty regarding the mechanism which enables swept trees to have reduced sweep with increasing diameter. If differential radial growth is the mechanism this has potential implications for the processing of logs which have had severe juvenile sweep. It is intended that the models developed will be made available to Forest and Farm Plantation Management Cooperative members through upgrades in STANDPAK.

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Christine Todoroki extracted pith and stem sinuosity data from the log database and provided useful information on data collection. Alex van Zyl extracted stand records for the logs used in this study. Alan Somerville kindly allowed access to cross sectional data. Mark Kimberley provided invaluable assistance with statistical analysis. Leith Knowles provided useful comments on a draft of this report. Thanks must be given to the Forest and Farm Plantation Management Cooperative and the Foundation for Research, Science and Technology for funding this project. The model coefficients are confidential to Cooperative members.

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