SENSITIVITY ANALYSIS OF LOG AND BRANCH CHARACTERISTICS INFLUENCING SAWN TIMBER GRADE

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ABSTRACT

An analysis of log and branch variables influencing timber grade outturn was performed using the AUTOSAW sawing simulator. Data from 115 unpruned *Pinus radiata* D. Don logs were used in the study; 85 logs were extracted from a plantation forest (Kaingaroa Forest) and the other 30 from a farm site (Tikitere Agroforestry Research Area).

Each log had been intensively measured and reconstructed as a virtual 3D log model inclusive of all branches. The virtual logs were repeatedly sawn with the sawing simulator over a range of rotational settings and product types. Virtual boards arising from the simulations were graded according to clear cuttings and visual structural grade requirements.

Simulated timber grades were correlated with indices reflecting log and branch characteristics. The sawn percentage of No. 2 cuttings and better grades (%2Cuts+) was correlated with combinations of traditional predictive variables and indices such as small-end diameter (SED), internode index (IIX), and mean internode length (MIL). New measures of internodal lengths, such as a fundamental internode length (FIL) that ignores whorls with three or fewer branches, were also trialled. FIL was developed on the premise that clearcuttings can be recovered that pass through whorls, especially when the branch count is low.

Models for predicting the sawn percentage of No. 1 Framing and better grades (%1F+) were correlated with Branch Index (BIX) and other log variables. Newly developed indices based on the sum of branch diameters within a whorl, such as WGB that refers to that whorl with the greatest sum of branch diameters, and knot size ratio (KSR), were fitted to both linear and non-linear regression models.

FIL gave higher correlations than IIX and MIL, when fitted using linear models, and in practice should be easier to calculate than MIL as whorls with three or fewer branches can be simply ignored. With non-linear regression models, the combination of IIX with SED gave the highest correlation. For predicting structural grade conversions, WGB gave higher correlations than BIX for both linear and nonlinear models. Almost as good a fit was achieved using WN4, which summed the branch diameters in the whorl with the most branches of 40 mm and over. In practice, WN4 is likely to be easier to use than the WGB. KSR was also effective in predicting sawn percentage of No. 1 Framing and better.

These results suggest that there is one whorl that has a significant influence on sawn percentage of No. 1 Framing and better grades.

Keywords: AUTOSAW; branch indices; internode index; log variables; sawing siumulation; timber grades.

INTRODUCTION

Predicting timber grade outturn for individual logs is extremely difficult. The difficulty arises because external characteristics provide only an indicative, rather than absolute, measure of internal characteristics and eventual board quality. Furthermore, predictions are based on a limited number of external characteristics that capture only a partial picture of the timber quality content of a log. Other difficulties arise from the interaction of factors such as genetics, seedlot, site, silviculture, primary processing, product specifications, and grading rule requirements. The interactions are complex and, needless to say, not fully understood. Attempts to understand the interactions are complicated by the unique characteristics of each log. Whilst certain characteristics are inherited through breeding, and others managed through silvicultural practices, each log is the result of dynamic biological processes. Each exhibits unique features — different shapes and sizes, branching patterns, and intrinsic wood properties.

The problem of predicting log conversions or sawn timber volumes, is basically one of geometry—cutting rectangular solids (sawn timber) from an irregular solid shape resembling a contorted truncated cone (the log). Log geometry is often described using the following variables:

- small-end diameter (SED)
- large-end diameter (LED)
- length (L)
- taper (TPR)
- sweep (SWP)

with the first variable, SED, providing much of the explanation for good correlations. However, the problem of predicting timber grades for any log is far more complex as log and branch geometry interact with primary processing factors.

Literature Review

Good descriptors of whorl and branch geometry are important as the largest influence on the quality and value yield of sawn timber can be attributed to the presence of various knots, their size, type, frequency, and location. Some of the descriptors that are currently used to indicate "branchiness" include branch index (BIX), internode index (IIX) (Inglis & Cleland 1982), and mean internode length (MIL) (Turner et al. 1997). BIX is used for predicting visual structural grade conversions, and IIX and MIL are associated with clear cuttings grades. Other intrinsic variables that influence quality include wood density, tracheid length, spiral grain, and heartwood to sapwood ratio.

Not only do these (and all aforementioned variables) vary from log to log, but also within a log. Further complexities are added to the problem at the primary processing stage. When the log is sawn into timber, yields are affected by processing mechanisms—e.g., sawpattern, sawkerfs, sawing variation, log positioning, orientation, and product dimensions. Variables that play a part in defining sawn timber grade are summarised in Table 1. The list is not exhaustive.

TABLE 1–Summary of variables influencing sawn yield

Log descriptors	
Log shape variables	SED, LED, length, taper, sweep, ovality, flare, wobble, swelling
Branching patterns	Whorl depth and number, branch size, number, orientation, internodes
Intrinsic variables	Wood density, tracheid length, spiral grain, heartwood:sapwood ratio
Processing variables	
Sawing method	Saw pattern and placement, log orientation and position
Machine variables	Scanning capability, number and placement of saws, kerfs, sawing variation
Sawn timber variables	Timber sizes, timber price list, timber grading rules

It is impractical, even under simulated conditions, to test every log under every processing scenario, and so this study focuses on variables that can be readily measured by non-destructive means, and controls processing variables using sawing simulation.

To link log variables to timber grades and value, Whiteside (1982) developed a series of regressions. The predictive models, incorporated in the Sawlog Evaluation Module of STANDPAK (Whiteside *et al.* 1989), were based on a series of sawing studies that were carried out under the charge of the Radiata Pine Task Force. In all, more than 400 logs were selected from a range of sites. Results from those studies identified the following variables as being significant:

- branch size index (BIX) (for the visual grading of unpruned logs)
- internode length index (IIX), small-end diameter (SED), and BIX (for cuttings grades from unpruned logs)
- SED and defect core diameter (for pruned logs)
- SED, taper, and sweep (when examining conversion percentages for both log types)
- sawpattern and mill conversion (conversion percentages, both log types).

These and other factors influencing timber recovery levels at a sawmill were cited by Steele (1984):

- sawing variation, rough green-lumber size, and size of dry-dressed lumber
- kerf width, product mix, sawing method
- decision-making by sawmill personnel
- condition and maintenance of mill equipment.

Because it is not possible to repeatedly saw the same log with a range of processing scenarios, computerised sawing simulators were developed. Using computer simulation, Richards (1973) examined alternative sawing methods; Hallock *et al.* (1979) compared centred and offset sawing patterns; and Maness & Donald (1994) and Todoroki (1995a) examined the effect of log rotation. Computer simulations have also been performed to investigate log conversion increases due to smaller kerfs at various machine centres, higher wane tolerances, different strategies and machine centre configurations (Todoroki 1994b, 1995b).

The above simulation studies focused on volume yield, and ignored the effect on grade or value. A series of simulations to evaluate the effect of different machine centre configurations on both volume and grade recoveries was undertaken by Todoroki (1994a). The trade-off between volume and value yield has been examined by Steele *et al.* (1993) for hardwood sawlogs, and by Todoroki & Rönnqvist (1999) for pruned *Pinus radiata* butt logs.

The latter investigation was performed using the sawing simulation system, AUTOSAW. Initially developed as a tool for assessing pruned log quality (Todoroki 1990), AUTOSAW has evolved into a system that "saws" log models with branches into boards with knot, pith, and wane defects (Todoroki 1997).

In this study, AUTOSAW was used to process a sample of unpruned logs under a range of conditions. Timber grades resulting from the simulations were compared with conventional log and branch variables and newly developed indices. Correlation coefficients and multiple regression models were calculated to determine which variables gave the best explanation for timber grade variation.

METHODS

In this section, characteristics of the log sample, and sawing and board grading methods are described. The log variables and indices are listed, together with definitions of the new predictive indices. Statistical methods used for data analysis are also described.

Log Sample

The log sample comprised 115 unpruned *Pinus radiata* logs, subsequently described as 3D virtual log models. The Kaingaroa plantation forest provided 85 logs and the Tikitere forest-farm site 30. The 85 plantation logs used in this analysis were extracted from two compartments at Kaingaroa Forest — Cpt 1350 and 375/RO 696. From the former compartment, 46 logs of varying log height classes (15 second, 10 third, 10 fourth, 8 fifth, 2 sixth, and 1 seventh log) were obtained from 15 stems. The remainder of the plantation logs were from Cpt 375 and were obtained from 14 stems (1 butt log, 14 second logs, 13 third logs, 9 fourth logs, 2 fifth logs). In contrast, all 30 farm-forestry logs were second logs. Log selection was based on branching characteristics. Logs were selected to cover as wide as possible a range of branch size (measured using BIX) and internode length (measured with IIX).

Sectional diameter measurements and location, orientation, and branch sizes were recorded for each log (C.MacLean pers. comm.). Summary statistics of log shape and size for the sample are given in Table 2, and summarised branch statistics of the log sample in Table 3 together with branch statistics obtained from the National Branch Database held at Forest Research.

On average the Tikitere logs were larger than those from Kaingaroa (refer Table 2) but had similar branch statistics (as indicated by BIX, IIX, etc., in Table 3). Further statistics of the log sample, with logs grouped by SED class, are given in the Appendix.

TABLE 2–Log sample statistics: size and shape

	Length (m)	SED (cm)	Taper (mm/m)	Sweep (mm)	Round log volume (m^3)
85-log Kaingaroa sample					
Av. ± s.d.	5.2±0.3	32±7	9±3	22±10	0.52±0.20
Min., Max.	4.7, 6.0	20, 53	1, 18	5, 55	0.21, 1.09
30-log Tikitere sample					
Av. ± s.d.	5.4±0.03	41±6	5±3	39±17	0.82±0.23
Min., Max.	5.4, 5.5	28, 50	0, 12	13, 86	0.42, 1.29

TABLE 3–Log sample statistics: branch size and distribution

	BIX (mm)	IIX	MIL (m)	No. whorls	Av. No. branches per whorl	Max. branch diam (mm)
85-log Kaingaroa sample						
Av. ± s.d.	52±14	0.22±0.22	0.41±0.20	10±3	6±1	63±19
Min., Max.	23, 98	0.00, 0.79	0.16, 1.10	4, 18	4, 9	32, 130
30-log Tikitere sample						
Av. ± s.d.	52±7	0.26±0.24	0.43±0.16	11±3	7±1	62±12
Min., Max.	37, 69	0, 0.81	0.21, 0.94	5, 19	4, 10	46, 100
National Branch Database statistics for Kaingaroa, log height classes 2…5						
Av. ± s.d.	51±13	0.22±0.09	0.43±0.16	9±2	6±1	60±17
Min., Max.	20, 120	0.00, 0.98	0.16, 1.85	1, 18	1, 13	20, 210

Sawing Methods

Simulated sawing

All virtual logs were repeatedly "sawn" using AUTOSAW. To facilitate comparisons and ensure consistency, standardised parameters were common to the simulations (Table 4). All logs were positioned for half-taper sawing and sawn using a cant sawing strategy. Cant size was dependent upon SED, with larger cants cut from larger logs. For logs with SED less than 25 cm a 100-mm cant (with 4-mm overcut) was cut; for logs greater than 35 cm, cant size was 200 mm (5-mm overcut); and for intermediary logs a 150-mm cant (5-mm overcut) was cut. A three-saw edger (producing one-or two-edged pieces) was assumed at the edging centre.

The 115 virtual logs were each "sawn" 24 times. Twelve log orientations were simulated: 0, 30, 60, … 330 degrees, for each of two product thicknesses — 40- and 50-mm boards.

TABLE 4–Primary and secondary settings

Machine centre	Sawkerf (mm)	Nominal board dimensions (mm)
Headrig	3	40 or 50 thick
Resaw	3	40 or 50 thick
Edger	3	50, 75, 100, 150, 200, 250, 300 wide

Simulated sawn timber produced from the intersection of sawcuts with parametric log and branch models (Todoroki 1997) displayed a variety of knots, pith, and wane defects. The virtual boards were automatically graded within AUTOSAW by invoking the algorithms for deriving grade according to the New Zealand Standard grading rules for Group III Exotic Softwoods (SANZ 1988). The 40-mm boards were graded according to appearance and clear cuttings grades (Clear, Select, No. 1 Cuttings, No. 2 Cuttings, Dressing, Merchantable, and Box grade requirements) and the 50-mm boards were graded according to visual structural grades (Engineering, No. 1 and No. 2 Framing, and Box).

The sawn percentage of No. 2 Cuttings and better grades was defined as:

$$\%2\text{Cuts+} = \frac{\text{Timber volume (Clear, Select, No.1 \& 2 Cuttings)}}{\text{Timber volume (Clear, Select, No.1 \& 2 Cuttings, Dressing, Merchantable, Box)}}\%$$

where the limiting or lowest grade in the numerator, No. 2 Cuttings, represents a piece that must be capable of yielding clear cuttings that are not less than 0.6 m long, and consist of at least 1.8 m of total clear cuttings, with these amounting to at least 70% of the total length of the piece.

For predicting the sawn percentage of No. 1 Framing and better grades the percentage was defined as:

$$\%1\text{F+} = \frac{\text{Timber volume (Engineering, No. 1 Framing)}}{\text{Timber volume (Engineering, No. 1 \& 2 Framing, Box)}}\%$$

The lower grade in the numerator, No. 1 Framing, consists of pieces that must satisfy the knot area ratio (KAR) criteria that represent the proportion of a cross-section occupied by a knot:

(1) KAR $\leq$ 1/3 knots either singly or in groups, in pieces not exceeding 150 mm wide

(2) KAR $\leq$ 1/4 knots either singly or in groups, in pieces exceeding 150 mm wide

(3) KAR $\leq$ 1/4 spike knots and double spike knots.

Other restrictions also apply (refer SANZ 1988).

For each log sawing simulation, log conversions were calculated by dividing the total sawn timber volume by the log volume. Log volume in turn was calculated with a series of truncated cones fitted between adjacent sectional diameter measurements. Timber volumes were calculated as the product of nominal width, nominal thickness, and board length.

Log Variables and other Predictive Indices

The variables and indices used in this study are listed in Table 5. Log size and shape variables and whorl counts were used in models for predicting %2Cuts+, and in models for predicting %1F+. Internodal variables were also used in the %2Cuts+ models, reflecting grading rule criteria. Development of Fundamental Internode Length (FIL) arose through the recognition that a whorl is not a solid mass of branches through which clearcuttings cannot be procured, but has potential to yield clearcuttings — especially when the branch count is low. For FIL, whorls with three or fewer branches are ignored. Those remaining internodes that are at least equal to the minimum length required for No. 2 Cuttings (60 cm) are summed, and the total is divided by the number of whorls (with four or more branches). Branch size variables were used in models for predicting %1F+. Like BIX, the whorl indices were

TABLE 5–Variables and other indices used to predict timber grade conversions

Variable/ Index	Definition
Log size and shape variables	
SED	Small-end diameter
SWP	Sweep – measured as maximum deviation from straightness
TPR	Taper = (LED – SED)/log length
LVOL	Log volume calculated from a series of cross-sectional diameter measurements
Branch and whorl counts	
NW	Number of whorls in log
Internodal variables	
SIL60+	Sum of internode lengths that are at least 60cm long
IIX	Internode Index = sum of internode lengths ≥ 60 cm divided by log length SIL60+/L
MIL	Mean internode length – sum of internodal lengths; divided by the number of whorls
AIL	Adjusted IL — as for SIL60+, but ignores whorls with fewer than four branches
FIL	Fundamental internode length – AIL / number of whorls with four or more branches
Branch size variables	
BIX	Branch Index — the average of the largest branch in each log quadrant
WGB	Sum of branch diameters in the whorl with the greatest sum of branch diameters
WLB	Sum of branch diameters in the whorl with the largest branch. When two or more whorls each have a branch equal in size to Maxbr, the sum of all branches is calculated for each, and the greatest total assigned to WLB.
WNB	Sum of branch diameters in the whorl with the maximum number of branches
WN4	Sum of branch diameters in the whorl with the greatest number of branches with diameter ≥ 4 cm
KSR	Knot size ratio = (SED – WGB) / SED

developed in an attempt to isolate the worst branches and/or whorls that were likely to influence grade outturn. By definition WGB is at least as great as each of WLB, WNB, and WN4.

Combinations of up to five variables (Table 6) were tested in models for predicting %1F+ and for predicting %2Cuts+.

Analysis of output

Simulated timber yield (averaged over the 12 rotational settings) from the repeated sawing simulations was used to examine:

- log conversion percentages
- timber grade percentages
- regression models for predicting %2Cuts+ from log variables
- regression models for predicting %1F+ from log variables.

Statistical analysis was performed using the SAS system (SAS Institute 1994). Linear regression models assumed the general form: $y = m_1x_1 + m_2x_2 + ... + b$; nonlinear regression models assumed the general form: $y = \exp(m_1x_1 + m_2x_2 + ... + b)$.

TABLE 6–Combinations of variables tested in multiple linear regressions

Variables used in predicting cuttings grades (% 2Cuts+)				
IIX	IIX, SED	IIX, SED, NW	IIX, SED, NW, SWP	IIX, SED, NW, SWP, TPR
MIL	MIL, SED	MIL, SED, NW	MIL, SED, NW, SWP	MIL, SED, NW, SWP, TPR
SIL60+	SIL60+, SED	SIL60+,SED, NW	SIL60+,SED, NW, SWP	SIL60+,SED, NW, SWP, TPR
AIL	AIL, SED	AIL, SED, NW	AIL, SED, NW, SWP	AIL, SED, NW, SWP, TPR
FIL	FIL, SED	FIL, SED, NW	FIL, SED, NW, SWP	FIL, SED, NW, SWP, TPR
Variables used in predicting visual structural grades (%1F+)				
BIX	BIX, SED	BIX, SED, NW	BIX, SED, NW, SWP	BIX, SED, NW, SWP, TPR
WGB	WGB, SED	WGB, SED, NW	WGB, SED, NW, SWP	WGB, SED, NW, SWP, TPR
WLB	WLB, SED	WLB, SED, NW	WLB, SED, NW, SWP	WLB, SED, NW, SWP, TPR
WNB	WNB, SED	WNB, SED, NW	WNB, SED, NW, SWP	WNB, SED, NW, SWP, TPR
WN4	WN4, SED	WN4, SED, NW	WN4, SED, NW, SWP	WN4, SED, NW, SWP, TPR
*	KSR	KSR, NW	KSR, NW, SWP	KSR, NW, SWP, TPR

* As KSR is calculated with two variables, WGB and SED, there is no single variable entry for KSR in the table

RESULTS

Log Conversion Percentages

Conversion percentages were calculated for each of the two product thicknesses and plantation sites (Fig. 1). It was apparent that overriding factors were:

- Log size — in general, the greater the SED the greater the conversion
- Product dimensions — smaller product dimensions enabled higher conversions.

There was still a reasonable amount of scatter, some of which can be explained by taper and sweep (refer Fig. 2). Median figures were used to define the taper and sweep classes. As the median taper was approximately 9 mm/m, moderately tapered logs were defined as those with taper > 9 mm/m.

Moderately swept logs were defined as those with a sweep deviation > 21 mm.

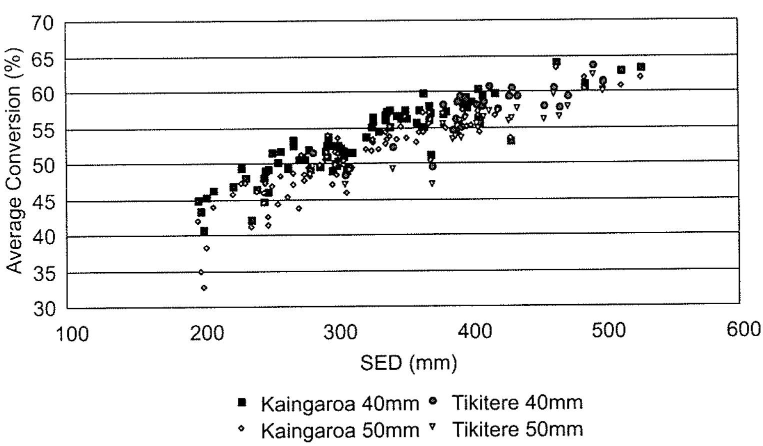

FIG. 1–Log conversion percentages by product thickness and plantation site (averaged over the 12 rotational settings)

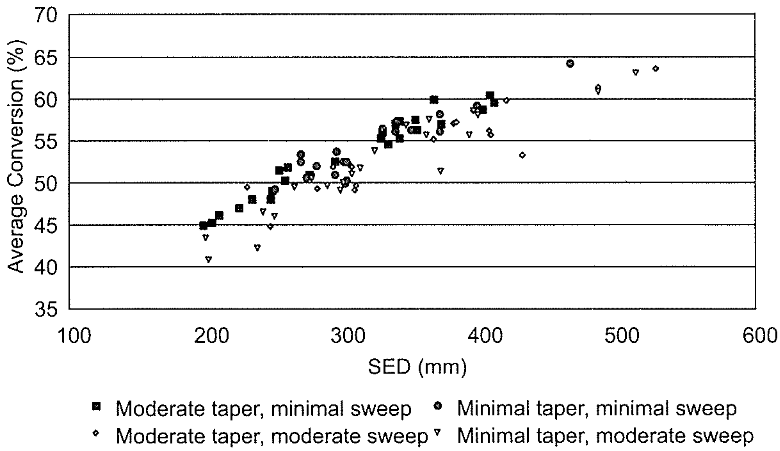

FIG. 2–Log conversion percentages (averaged) for 40-mm products

Timber Grade Percentages

Contrasting examples of timber grade conversion percentages for the 12 log orientations are shown in Fig. 3. The logs were selected from the sample to cover low, medium, and high instances of IIX (0.2, 0.6, 0.8) and a range over BIX from 4 to 8 cm. Appearance and cuttings grades are shown in the lefthand column and visual structural grades on the right. Logs 85 and 91, with the same IIX of 0.2, demonstrated similar appearance and cuttings grade conversions, but quite different structural grade conversions. Sensitivity of the grade distributions according to log orientation can be seen in Fig. 3. Different proportions of grades, with different starting log orientations, were apparent. In addition to within-log variation, between-log variation was clearly evident. The orientation yielding the greatest recovery of high-valued products varied from log to log. Further, log 85 with a BIX of 42 mm and SED of 27 cm produced on average a lower percentage of No. 1 Framing and better grades than log 67 with a BIX of 51 mm and SED of 37 cm. The next two sections try to isolate those variables that are significant in their contribution to the differing between-log grade distributions.

Regression Models for Predicting the Percentage of No.2 Cuttings and Better Grades from Log Variables

Coefficient of determination, R^2 values, determined by fitting linear multiple regression models to combinations of variables, are shown in Table 7. The R^2 values are shown in bold type for those models for which all variables within the combination are significant. For single variable indicators, FIL gave the best fit ($R^2 = 0.69$ for 115-log sample), MIL recorded an R^2 value of 0.62, and IIX a value of 0.53. Adding SED to each of these models gave improved fits, and the combination of FIL and SED recorded an R^2 value of 0.72. Addition of further variables, NW, TPR, and SWP, did not generally provide any significant improvements to the regression statistics.

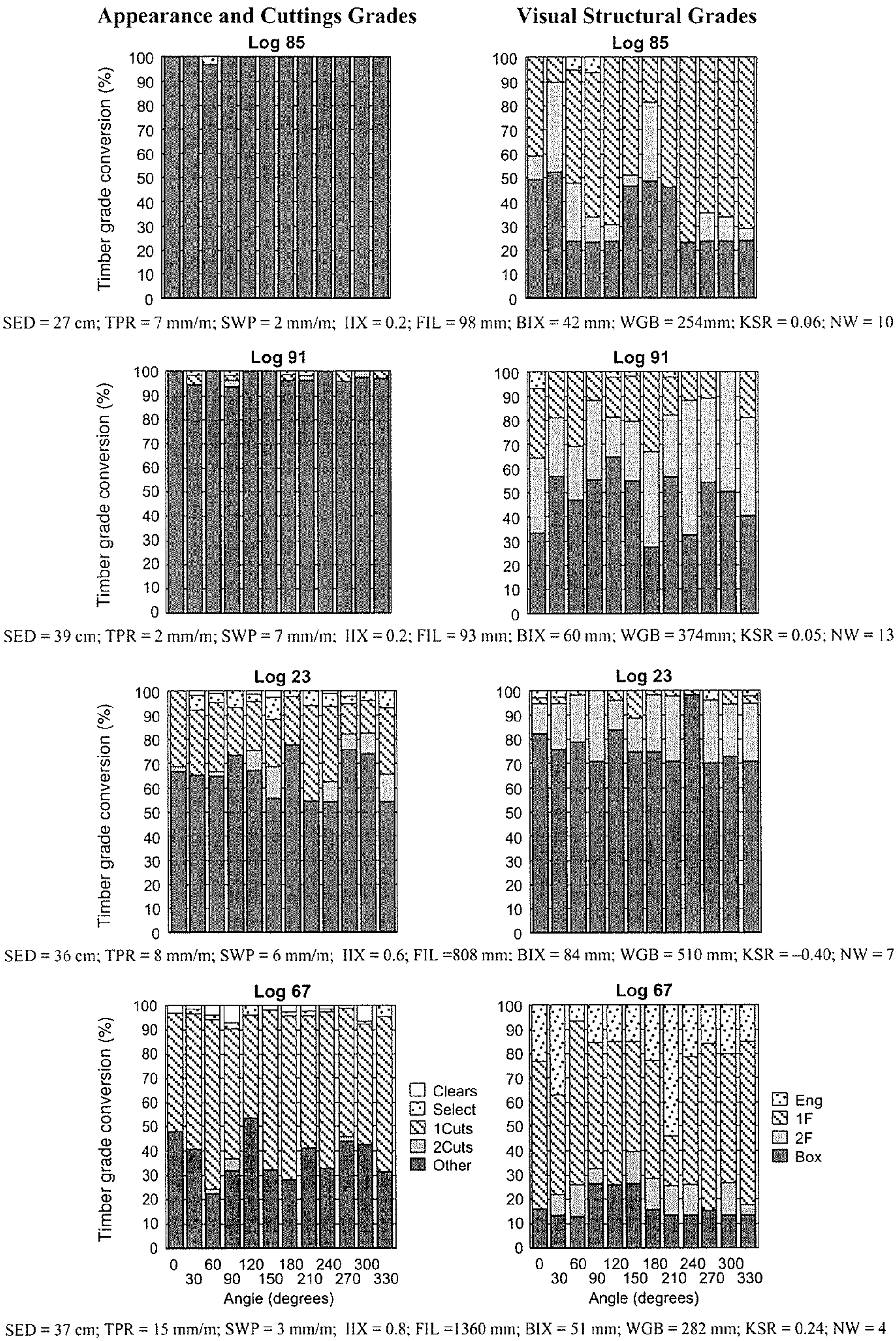

FIG. 3–Grade distributions obtained from different log orientations

TABLE 7–R^2 values for linear models predicting %2Cuts+ (shown in bold when all variables in model are significant)

Variable combination	115 log sample	K85 logs*	T30 logs*	Model
FIL, SED, NW,SWP,TPR	0.73	0.80	0.75	
FIL, SED, NW, SWP	0.73	0.80	0.75	
FIL, SED, NW	0.72	0.79	0.75	
FIL, SED	**0.72**	**0.79**	**0.75**	**Model D**
FIL	**0.69**	**0.77**	**0.60**	**Model C**
MIL, SED, NW,SWP,TPR	0.69	0.76	0.70	
MIL, SED, NW, SWP	0.67	0.75	0.70	
MIL, SED, NW	**0.66**	**0.75**	0.70	
MIL, SED	**0.64**	**0.72**	0.61	
MIL	**0.62**	**0.68**	**0.57**	**Model B**
IIX, SED, NW,SWP,TPR	0.59	0.59	0.66	
IIX, SED, NW, SWP	0.58	0.58	0.66	
IIX, SED, NW	0.58	0.58	0.65	
IIX, SED	**0.58**	**0.58**	**0.65**	
IIX	**0.53**	**0.53**	**0.46**	**Nodel A**
SIL60+,SED, NW,SWP,TPR	0.58	0.57	0.66	
SIL60+,SED, NW, SWP	0.57	0.56	0.66	
SIL60+,SED, NW	0.57	0.56	0.66	
SIL60+,SED	**0.56**	**0.56**	**0.66**	
SIL60+	**0.52**	**0.50**	**0.47**	
AIL, SED, NW,SWP,TPR	0.56	0.55	0.63	
AIL, SED, NW, SWP	0.54	0.54	0.63	
AIL, SED, NW	**0.54**	**0.54**	0.62	
AIL, SED	**0.52**	**0.52**	**0.61**	
AIL	**0.45**	**0.44**	**0.37**	

* K85 = 85 logs from Kaingaroa Forest
T30 = 30 logs from Tikitere Agroforestry Research Area

Additional regression statistics for four of the models (based on the 115-log sample) are given below:

Model A: %2Cuts+ = f (IIX) **$R^2 = 0.53$** **$p << 0.01$**

F	Df	Ssreg	Ssresid
131	113	20314	17462

Model B: %2Cuts+ = f (MIL) **$R^2 = 0.62$** **$p << 0.01$**

F	df	Ssreg	Ssresid
182	113	23310	14467

Model C: %2Cuts+ = f (FIL) **$R^2 = 0.69$** **$p << 0.01$**

F	df	Ssreg	Ssresid
254	113	26160	11616

Model D: %2Cuts+ = f (FIL, SED) **$R^2 = 0.72$** **$p << 0.01$**

F	df	Ssreg	Ssresid
143	112	27156	10620

In each of the above models the p-value is well below 0.01. Therefore we have strong evidence to reject the null hypothesis and to conclude that the above variables do have significant predictive value. Graphs of predicted against actual values for Models A, B, C, and D are given in Fig. 4. The dark line lies at y = x, whilst the lighter line shows the fit of the linear regression. For each of the models the linear regression lies below the y = x line, indicating that the models under-predict %2Cuts+.

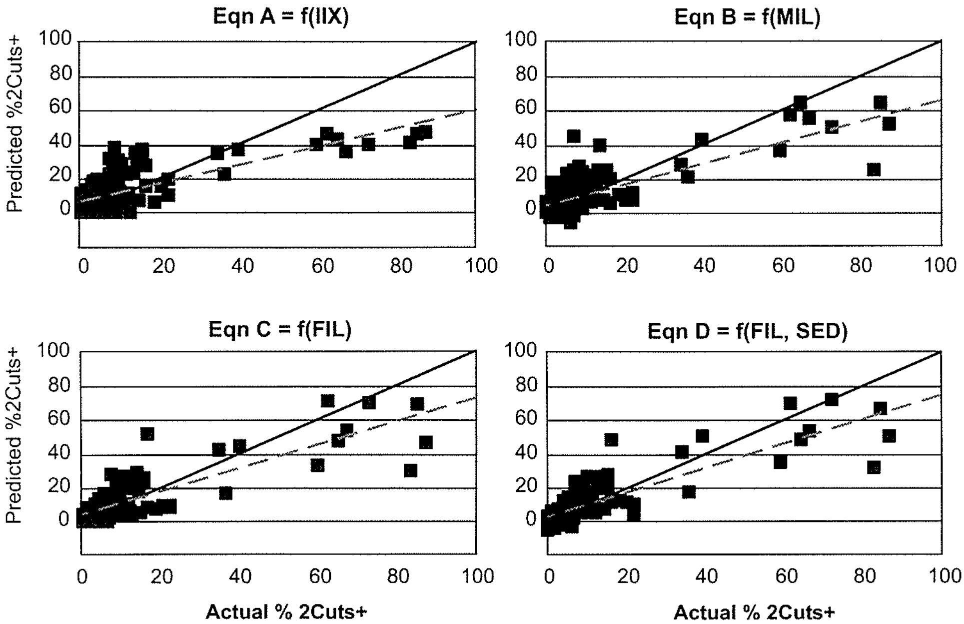

FIG. 4—Plots of actual %2Cuts+ against predicted values using Models A, B, C, and D

Nonlinear regression statistics are given in Table 8. For models that included variables IIX, SIL60+, or AIL, the non-linear models provided significantly better fits (as indicated by the higher R^2 values) than their linear counterparts. Improvement with use of non-linear models was also noted for models containing MIL. For non-linear regressions using FIL together with combinations of the variables SED, NW, SWP, and TPR, high correlations were recorded. This was particularly marked for the 30-log sample with an R^2 value of 0.94. Values of 0.94 or 0.95 were recorded for all five-variable models with the exception of the MIL model.

Regression Models for Predicting the Percentage of No. 1 Framing and Better Grades from Log Variables

Variables used in regression models for predicting %1F+ are given in the upper part of Table 9, with R^2 values for both linear and non-linear models presented in the lower part of the table. Once again the bold type indicates those models for which all variables are significant. Unlike models for predicting %2Cuts+, non-linear models for predicting %1F+

TABLE 8–R^2 values for non-linear models predicting %2Cuts+ (shown in bold when all variables in model are significant)

Variable combination	115 log sample	K85 logs*	T30 logs*
FIL, SED, NW,SWP,TPR	0.80	**0.88**	**0.94**
FIL, SED, NW, SWP	**0.80**	**0.87**	0.77
FIL, SED, NW	**0.74**	**0.86**	0.76
FIL, SED	**0.68**	**0.81**	0.76
FIL	**0.64**	**0.78**	**0.76**
MIL, SED, NW,SWP,TPR	0.74	0.82	0.70
MIL, SED, NW, SWP	0.74	0.82	0.68
MIL, SED, NW	**0.73**	0.82	0.68
MIL, SED	**0.72**	**0.82**	**0.64**
MIL	**0.66**	**0.78**	**0.61**
IIX, SED, NW,SWP,TPR	0.83	0.82	0.95
IIX, SED, NW, SWP	0.82	0.81	0.89
IIX, SED, NW	0.82	**0.81**	**0.89**
IIX, SED	**0.82**	**0.79**	**0.86**
IIX	**0.78**	**0.74**	**0.84**
SIL60+,SED, NW,SWP,TPR	0.82	0.82	**0.95**
SIL60+,SED, NW, SWP	0.81	0.81	0.90
SIL60+,SED, NW	**0.81**	**0.81**	0.88
SIL60+,SED	**0.77**	**0.76**	**0.87**
SIL60+	**0.74**	**0.68**	**0.85**
AIL, SED, NW,SWP,TPR	0.83	0.84	**0.94**
AIL, SED, NW, SWP	0.82	0.83	0.88
AIL, SED, NW	**0.81**	**0.83**	0.87
AIL, SED	**0.74**	**0.68**	**0.87**
AIL	**0.69**	**0.60**	**0.85**

* K85 = 85 logs from Kaingaroa Forest
T30 = 30 logs from Tikitere Agroforestry Research Area

provided no benefits over linear models. All models with WGB, WN4, and KSR recorded higher correlation coefficients than models containing BIX. In addition to SED, the number of whorls, taper, and sweep showed significant predictive value in many of the models.

The regression using BIX and SED, which is closest to the current SAWMOD model, explained about 60% of the variation in simulated "green" yield. The best stand-alone branch variable tested was KSR. The addition of further variables gave small improvements. Good fits were obtained with WGB, SED, and other variables, explaining more than 70% of the variation in simulated grades. Almost as good a fit was achieved using WN4, which summed the branch diameters in the whorl containing the most branches of 40 mm and over. In practice, the WN4 model is likely to be easier to use than the WGB model.

Further regression statistics for four of the linear models, based on the 115-log sample, are given below:

Model E: %1F+ = f (BIX, SED) **$R^2 = 0.60$** **$p << 0.01$**

F	df	Ssreg	Ssresid
83	112	34245	23153

TABLE 9–R^2 values obtained with multiple linear & non-linear regression models predicting %1F+ (shown in bold when all variables in model are significant)

Variables used in predicting visual structural grades (%1F+)

1,1 BIX	1,2 BIX, SED	1,3 BIX, SED, NW	1,4 BIX, SED, NW, SWP	1,5 BIX, SED, NW, SWP, TPR
2,1 WGB	2,2 WGB, SED	2,3 WGB, SED, NW	2,4 WGB, SED, NW, SWP	2,5 WGB, SED, NW, SWP, TPR
3,1 WLB	3,2 WLB, SED	3,3 WLB, SED, NW	3,4 WLB, SED, NW, SWP	3,5 WLB, SED, NW, SWP, TPR
4,1 WNB	4,2 WNB, SED	4,3 WNB, SED, NW	4,4 WNB, SED, NW, SWP	4,5 WNB, SED, NW, SWP, TPR
5,1 WN4	5,2 WN4, SED	5,3 WN4, SED, NW	5,4 WN4, SED, NW, SWP	5,5 WN4, SED, NW, SWP, TPR
6,1*	6,2 KSR	6,3 KSR, NW	6,4 KSR, NW, SWP	6,5 KSR, NW, SWP, TPR

Variable indexing row, column (refer above for combinations)	**R^2 values for linear regression models**			**R^2 values for non-linear regression models**		
	115 logs	K85 logs	T30 logs	115 logs	K85 logs	T30 logs
1,1	**0.38**	**0.42**	**0.24**	**0.37**	**0.65**	**0.22**
1,2	**0.60**	**0.63**	**0.64**	**0.59**	**0.68**	**0.60**
1,3	0.60	0.63	0.65	0.59	**0.71**	0.61
1,4	0.63	**0.67**	0.65	0.62	**0.73**	0.61
1,5	0.66	**0.69**	0.67	0.64	0.68	0.64
2,1	**0.47**	**0.50**	**0.47**	**0.44**	**0.48**	**0.41**
2,2	**0.71**	**0.70**	**0.79**	**0.65**	**0.64**	**0.69**
2,3	**0.73**	**0.74**	0.79	**0.67**	**0.69**	0.69
2,4	**0.75**	**0.76**	0.81	**0.69**	**0.71**	0.73
2,5	**0.76**	**0.77**	0.84	**0.70**	**0.74**	0.77
3,1	**0.23**	**0.27**	0.15	**0.23**	**0.27**	**0.13**
3,2	**0.44**	**0.48**	0.44	**0.42**	**0.48**	0.40
3,3	**0.49**	**0.55**	0.45	**0.47**	**0.56**	0.41
3,4	**0.53**	**0.59**	0.49	**0.53**	**0.59**	0.49
3,5	0.53	0.59	0.50	0.53	0.60	0.50
4,1	**0.28**	**0.33**	0.19	**0.25**	**0.31**	0.16
4,2	**0.51**	**0.50**	**0.69**	**0.50**	**0.49**	**0.65**
4,3	**0.54**	**0.55**	0.72	**0.52**	**0.53**	0.65
4,4	0.54	0.55	0.72	0.53	0.53	0.67
4,5	0.55	0.56	0.73	0.53	0.54	0.68
5,1	**0.43**	**0.45**	**0.46**	**0.40**	**0.43**	**0.40**
5,2	**0.68**	**0.66**	**0.76**	**0.62**	**0.61**	**0.66**
5,3	**0.71**	**0.71**	0.76	**0.65**	**0.67**	0.66
5,4	**0.73**	**0.73**	0.78	**0.68**	**0.71**	0.69
5,5	**0.74**	0.75	0.82	0.68	**0.72**	0.74
6,1	*	*	*	*	*	*
6,2	**0.66**	**0.65**	**0.80**	**0.66**	**0.65**	**0.71**
6,3	0.68	**0.68**	0.80	**0.68**	**0.68**	0.71
6,4	0.71	**0.71**	0.82	**0.70**	**0.71**	0.73
6,5	**0.72**	0.72	0.86	**0.71**	**0.73**	0.77

* As KSR is calculated from two variables, WGB and SED, there is no single variable entry at 6,1

Model F: %1F+ = f (NW, WGB, SED) **$R^2 = 0.73$** **$p \ll 0.01$**

F	df	Ssreg	Ssresid
103	112	42180	15218

Model G: %1F+ = f (WGB, NW, SWP, SED, TPR) **$R^2 = 0.76$** **$p \ll 0.01$**

F	df	Ssreg	Ssresid
71	109	43862	13536

Model H: %1F+ = f (WN4, NW, SWP, SED, TPR) **$R^2 = 0.74$** **$p \ll 0.01$**

F	df	Ssreg	Ssresid
61	109	42252	15146

Since the *p*-values are well below 0.01 we can conclude that the above combinations of variables collectively have some predictive value. Note that Model E is similar to the SAWMOD model. Model F gave the best fit using three variables (for the 115-log sample) and indicates that there is one whorl (WGB) that has a significant influence.

However, there is an additional effect from other whorls in the log as suggested by the significance of the negative coefficient of NW. The best overall fits came from adding variables for log shape, i.e., sweep and taper (Models G and H). Model H suggests that the whorl with the most large branches (i.e., branches ≥ 40 mm) is also a good indicator of timber grade.

DISCUSSION

The above simulation exercises have shown consistencies with earlier findings from actual sawing studies — namely, that log size and shape as expressed by SED, sweep, and taper have a significant influence on timber recovery levels. The effect of product mix on conversions was also observed and was consistent with earlier findings.

Although the effect of log rotation on volume yield has been examined previously (Todoroki 1995a), here differences in grade recovery were demonstrated over 12 initial log orientations. The average of the 12 orientations was used to determine relationships between grade recoveries and external log and branch characteristics for between-log comparisons, but further investigation is required to quantify the effect of branching on within-log grade distributions. With adequate knowledge of the branching structure and its effects on yield, it could be possible to orientate and then place the log for optimal recovery of high-valued products.

The testing of regression models for predicting %2Cuts+ suggested that non-linear models may be more effective than their linear counterparts. The commonly used IIX, SED combination provided was an example of this. However, if linear models are to be used, then the new variable FIL shows good predictive potential. In practice FIL is as easy to calculate as either IIX or MIL, if not easier, as whorls with fewer than four branches can simply be ignored.

On the other hand, non-linear models showed no benefit over linear models for predicting %1F+. Results suggested that there may be better indices for predicting %1F+ than the commonly used BIX. Overall, better correlations were found for WGB, WN4, and KSR (also based on WGB) than for BIX. All these new whorl indices (Wxx) perform the same basic function — i.e., they sum the branch diameters in a given whorl. This leads us to speculate that a log may have one whorl in particular that has a significant influence on the proportion of %1F+. While total branch size captures one property of a whorl, other whorl properties may also be important. The location of a whorl within a log could also influence %1F+. A new index that takes into account only those whorls that are within a specified distance from the log ends could be developed and subjected to further investigation.

This study provided an initial investigation into the analysis of external log and branch variables on internal log quality and subsequent timber grade conversions. As suggested above, there remains much scope for expansion. Further exploration into areas as diverse as trait selection, log allocation, and log sawing optimisation is possible. A study that uses manually graded timber from a sawmill study, as opposed to simulated yield, will be the subject of further investigation. If similar results are found then new indices such as WGB or WN4 could be considered for inclusion in decision support software or field tools for the forestry industry.

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APPENDIX

LOG SAMPLE STATISTICS

For ease of identification the Tikitere logs are indicated separately, after the "+" sign. Standard mathematical notation (i.e., "(" representing the open interval, and "]" representing the closed interval) is used to describe SED intervals, e.g., (25–30] ≡ 25 < SED ≤ 30 cm.

TABLE A1–Frequency by SED (cm) and log height class

SED	Log height class							Total
(cm)	1	2	3	4	5	6	7	
≤ 25	0	2	2	7	3	1	0	15
(25–30]	1	1+2	7	5	4	1	1	20+2
(30–35]	0	8+3	7	5	1	0	0	21+3
(35–40]	0	9+9	5	1	2	0	0	17+9
(40–45]	0	5+9	1	1	0	0	0	7+9
> 45	0	4+7	1	0	0	0	0	5+7
Total	1	29+30	23	19	10	2	1	85+30

TABLE A2–Frequency by SED (cm) and log length (m)

SED	Length (m)					Total
(cm)	4.7–4.9	5.0–5.2	5.3–5.5	5.6–5.8	5.9–6.1	
≤ 25	6	1	6	1	1	15
(25–30]	10	1	7+2	2	0	20+2
(30–35]	10	2	7+3	2	0	21+3
(35–40]	10	1	5+9	0	1	17+9
(40–45]	3	1	1+9	2	0	7+9
> 45	4	1	0+7	0	0	5+7
Total	43	7	26+30	7	2	85+30

TABLE A3–Frequency by SED (cm) and taper (mm/m)

SED	Taper (mm/m)				Total
(cm)	< 5	[5, 10)	[10, 15)	[15, 20)	
≤ 25	0	9	5	1	15
(25–30]	2	14+2	4	0	20+2
(30–35]	1+1	11+2	9	0	21+3
(35–40]	3+4	10+5	3	1	17+9
(40–45]	0+4	3+5	1	3	7+9
> 45	1+2	3+2	1+3	0	5+7
Total	7+11	50+16	23+3	5	85+30

TABLE A4–Frequency by SED (cm) and sweep (mm)

SED	Sweep (mm)						Total
(cm)	< 12	[12, 24)	[24, 36)	[36, 48)	[48, 60)	≥ 60	
≤ 25	2	7	5	0	1		15
(25–30]	4	7+1	5+1	1	3		20+2
(30–35]	4	10+1	6	0	1+2		21+3
(35–40]	1	7+1	8+4	1+2	0+1	+1	17+9
(40–45]	0	3+3	4+4	0+1	0	+1	7+9
> 45	1	1	1	2+3	0+3	+1	5+7
Total	12	35+6	29+9	4+6	5+6	+3	85+30

TABLE A5–Frequency by SED (cm) and IIX

SED (cm)	IIX < 0.2	[0.2, 0.4)	[0.4, 0.6)	[0.6, 0.8)	Total
≤ 25	12	3	0	0	15
(25–30]	9+1	6	4	1+1	20+2
(30–35]	15	1+2	3+1	2	21+3
(35–40]	8+5	4+4	2	3	17+9
(40–45]	3+4	2+1	0+2	2+2	7+9
> 45	3+5	0+1	0	2+1	5+7
Total	50+15	16+8	9+3	10+4	85+30

TABLE A6–Frequency by SED (cm) and FIL (mm)

SED (cm)	FIL (mm) < 200	[200, 400)	[400, 600)	≥ 600	Total
≤ 25	15	0	0	0	15
(25–30]	12+1	4	3+1	1	20+2
(30–35]	13+1	5+1	2+1	1	21+3
(35–40]	11+8	2+1	1	3	17+9
(40–45]	5+3	1+3	0+2	1+1	7+9
> 45	3+6	0	0	2+1	5+7
Total	59+19	12+5	6+4	8+2	85+30

TABLE A7–Frequency by SED (cm) and BIX (mm)

SED (cm)	BIX (mm) [20, 40)	[40, 60)	[60, 80)	[80, 100)	Total
≤ 25	5	5	5	0	15
(25–30]	3	11+2	6	0	20+2
(30–35]	6+1	7+2	8	0	21+3
(35–40]	3	8+8	5+1	1	17+9
(40–45]	2	2+7	2+2	1	7+9
> 45	2	3+7	0	0	5+7
Total	21+1	36+26	26+3	2	85+30

TABLE A8–Frequency by SED (cm) and WGB (mm)

SED (cm)	WGB (mm) < 200	[200, 250)	[250, 300)	≥ 300	Total
≤ 25	6	5	2	2	15
(25–30]	2	8	5+1	5+1	20+2
(30–35]	7+1	3+2	5	6	21+3
(35–40]	3+1	3+3	5+2	6+3	17+9
(40–45]	2+1	0+4	3+2	2+2	7+9
> 45	3	1+4	0+1	1+2	5+7
Total	23+3	20+13	20+6	22+8	85+30