Log segregation for a structural lumber mill based on stand location and log position within trees

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Abstract

For the wood processing value chain to operate efficiently and profitably, processors need to obtain the wood raw material resource best suited to their needs. This may mean wood suppliers identifying and segregating stands and logs based on internal wood properties, as well as log external properties. A techno-economic model was developed that allowed calculation of mill-gate return-to-log (RTL) values ($/m^3) based on log external characteristics and wood density. Stem descriptions from eight stands located in four wood supply regions around New Zealand were input to the model. Data from 8,271 logs were output from the model and segregated into groups based on stand location, small end diameter (SED) classes and position up the stem where the log was cut.

There were statistically significant differences in RTL due to stand location, SED and log position. For a given log SED class, RTL was shown to differ between stands and to decrease with height up the stem. These differences are due to differences in the wood density of the logs between stands and between positions in the stems. Individual log identification (log ID) may provide an opportunity for forest owners and wood processors to segregate logs based on wood property differences and to potentially share improvements in value recovery.

Introduction

The Forest Growers Research programme Te Mahi Ngahere i te Ao Hurihuri – Forestry Work in the Modern Age commenced on 1 January 2019. The programme outlines a pathway for the New Zealand forest industry to develop innovative harvesting technologies in forestry automation and robotics that will address labour shortages, reduce forestry value chain costs, improve the economic viability of harvesting small forests, and enhance long-term sustainability through reducing environmental impact and making harvesting jobs safer for workers (Forest Growers Research, 2018).

One of the projects within the research programme is the development of an automated individual log ID tagging and tag reading system. Individual log ID has great potential for improving production efficiencies in the log value chain from stump to port or ex-mill gate. These systems can ensure that the right log product is allocated to the end product for which it is best suited, and they can help to control costs and maximise customer service. Tagging and tracking of logs is a common practice within export log supply chains, but it is little used within domestic log supply chains in New Zealand.

For the wood processing value chain to operate efficiently and profitably, processors need to obtain the wood raw material resource best suited to their needs (Murphy et al., 2010). This may mean identifying and segregating stands and logs based on internal wood properties, as well as log external properties (Manley, 2002).

A large European programme, called Indisputable Key, looked at developing tagging and tracking systems for forestry supply chains in Europe. It emphasised the importance of quantifying the benefits of such systems for wood processors and forest owners. The Indisputable Key programme demonstrated, for example, that timber drying times could be reduced by 4% if wood could be classified as either 'low' or 'high' density. It also demonstrated that segregating logs based on stand location could yield increases in lumber volume recovery, lumber grade recovery and sawmill productivity (Uusijarvi, 2010).

Historically, trees have been converted into logs and these are sorted based on external attributes such as diameter, length, straightness, branch size and the presence of obvious defects such as end checks, decay and resin bleeding. While these attributes affect the yields of products that can be obtained by a mill, they have little impact on end product performance, which is mostly driven by the internal wood properties of logs.

Processing operations differ in their wood raw material requirements, depending on the product that they are making (Moore & Cown, 2015). Mills making structural products (such as dimension lumber, glue-laminated lumber and laminated veneer lumber) generally require logs that will give high yields of products with acceptable stiffness and low warp (Perstorper et al., 1995). Wood density has been shown to affect stiffness, twist (Cown et al., 2004) and structural lumber grade recoveries (Wood Quality Initiative Ltd, unpublished data).

Over 95% of the plantation forest volume harvested in New Zealand is cut into logs using mechanised processing machines (Visser & Obi, 2020). Most of the mechanised log processors use the Standard for Forest machine Data and communication (StanForD) protocol for recording log data (Skogforsk, 2007). Among the many attributes that can be linked to each log are the stand from which the log was harvested, its grade, its small and large end diameters, its length and its location up the stem. An individual log ID number can also be allocated to the log and stored in the StanForD files.

This paper explores the effect of one internal wood property (density) on the variation in mill-gate return-to-log (RTL) values arising from differences between stands and positions within stems. If there are significant differences in RTL values, there may be benefits for tagging individual logs in domestic supply chains, as well as in export supply chains.

Methods and materials

Model description

The techno-economic model SEGMOD, described by Murphy and Moore (2018), was used with trivial modifications to derive mill-gate RTL values based on external and internal log and wood properties for a representative mill cutting structural lumber.

RTL value is not market price, which will depend upon many things, including the general supply and demand for logs with particular attributes and the current financial position of individual buyers (Kininmonth, 1987). RTL values are indicators, however, of the potential worth of logs to buyers. Mill-gate RTL values, expressed on a per cubic metre basis, were calculated for each log using the following equation:

Mill-gate RTL ($/m^3) = (Total Value of Products – Processing Costs)/Log Volume – Mill Yard Costs

where:

*Total Value of Products ($) = (Lumber Value + Chip Value + Hog Fuel Value) * (1-Margin for Profit)*

Lumber Value ($) = Volume Conversion Factor $\sum_{i=1}^{n}$ LumberGrade%$_i$*LumberPrice$_i$*

*Chip Value ($) = (1- Volume Conversion Factor) * Chip% * Chip Price*

*Hog Fuel Value ($) = (1- Volume Conversion Factor) * Hog% * Hog Fuel Price*

Volume Conversion Factor (ratio) = Proportion of log volume converted to lumber

LumberGrade%$_i$ = % volume in ith lumber grade

LumberPrice$_i$ ($/m^3) = price of ith lumber grade

Chip% = % of wood waste suitable for chips

Hog% = % of wood waste suitable for hog fuel

Volume conversion factors (% of log volume converted to lumber) for the structural grade mill were based on radiata pine sawing studies carried out by the New Zealand Forest Research Institute in the 1980s (Cown et al., 1987). Small end diameter (SED), sweep and taper were the key parameters in the deterministic equation used to calculate the volume conversion factor. Volume conversion factors used in our analyses also included a timber-loss factor (7%). Chip and hog percentages were assumed to be equivalent to 75% and 25% of the non-lumber volume, respectively. The margin for profit was assumed to be 7.5%.

Radiata pine structural lumber grade recoveries were based on models fitted to data from mill studies undertaken using logs from radiata pine stands in the Central North Island of New Zealand (Wood Quality Initiative Ltd, unpublished data). Wood density is the key driver of grade recovery in these deterministic models, which predict the percentage of recovered volume in each of the New Zealand structural timber grades (Standards New Zealand, 1993). Other non-dimensional log quality attributes are not drivers in these models.

The following prices used in the model are averages from four regional price and cost datasets assembled in 2017:

- Lumber prices: MSG12 + $635/m^3, MSG10 $605/m^3, MSG8 $555/m^3, MSG6 $395/m^3 and MSG<6 $290/m^3
- Chip price: $52/m^3 solid wood equivalent
- Hog fuel price: $11/m^3 solid wood equivalent
- Log processing costs: $140 per m^3 of output
- Mill yard costs: $2.50 per m^3 of input.

These data may have changed slightly since then but are sufficient for determining relative differences in mill-gate RTL values, if not absolute differences.

Log data

Log data were derived from eight stands in four different regions within New Zealand (Figure 1). Table 1 summarises basic information for the eight stands.

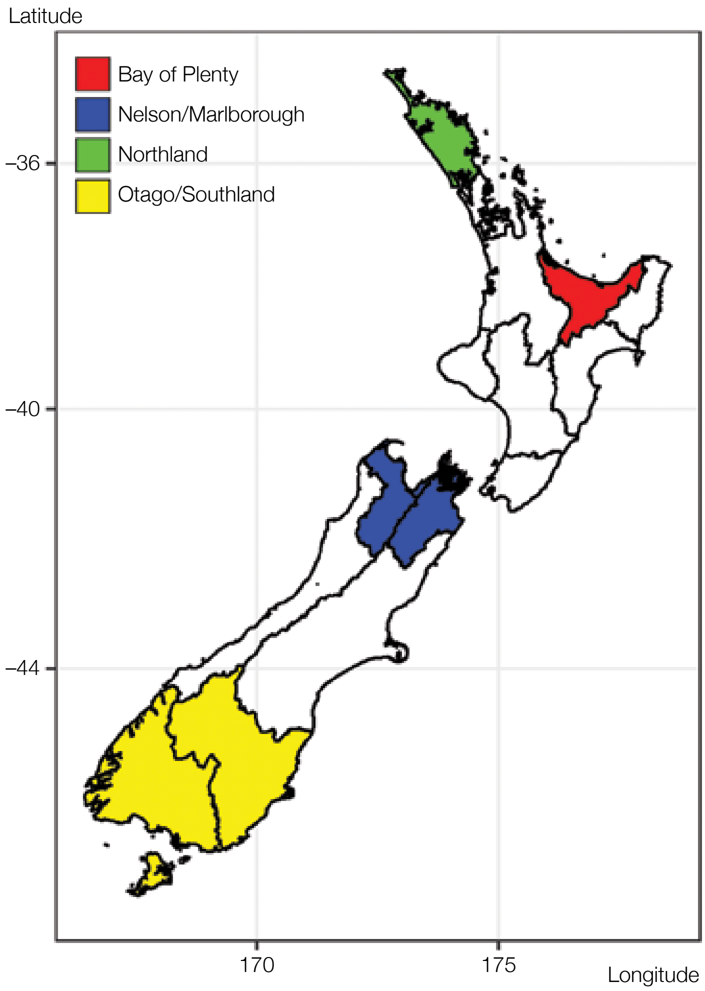

Figure 1: Location of the four study regions in NZ. Source: Murphy & Moore, 2018

Table 1: Basic stand data for eight stands located in four regions

	Region							
	Northland		Bay of Plenty		Nelson/Marlborough		Otago/Southland	
Stand ID	I	II	III	IV	V	VI	VII	VIII
Age (years)	24	24	28	25	25	24	29	27
Stand density (stems/ha)	434	338	324	504	493	502	276	299
Merchantable tree size (m^3)	1.65	1.77	2.08	1.48	1.71	1.20	2.08	1.94
Breast height outer-wood density (kg/m^3)	466	442	421	410	431	420	404	395

Detailed stem descriptions from standard pre-harvest inventory assessments were provided by forest owners for two representative radiata pine stands in each of the four regions. Breast height outer-wood density information (mean and standard deviation), if available, were provided by the forest owners. Where wood density information was not available, it was predicted from national models (Palmer et al., 2013; Kimberley et al., 2015) based on stand location and age (e.g. see Figure 2).

Wood density values measured (or predicted) at breast height were stochastically allocated to individual trees within each stand based on the means and standard deviations. These were then extrapolated to other heights in the tree stems using non-linear functions (see Equation (3) and Figure 5 in Kimberley et al., 2015).

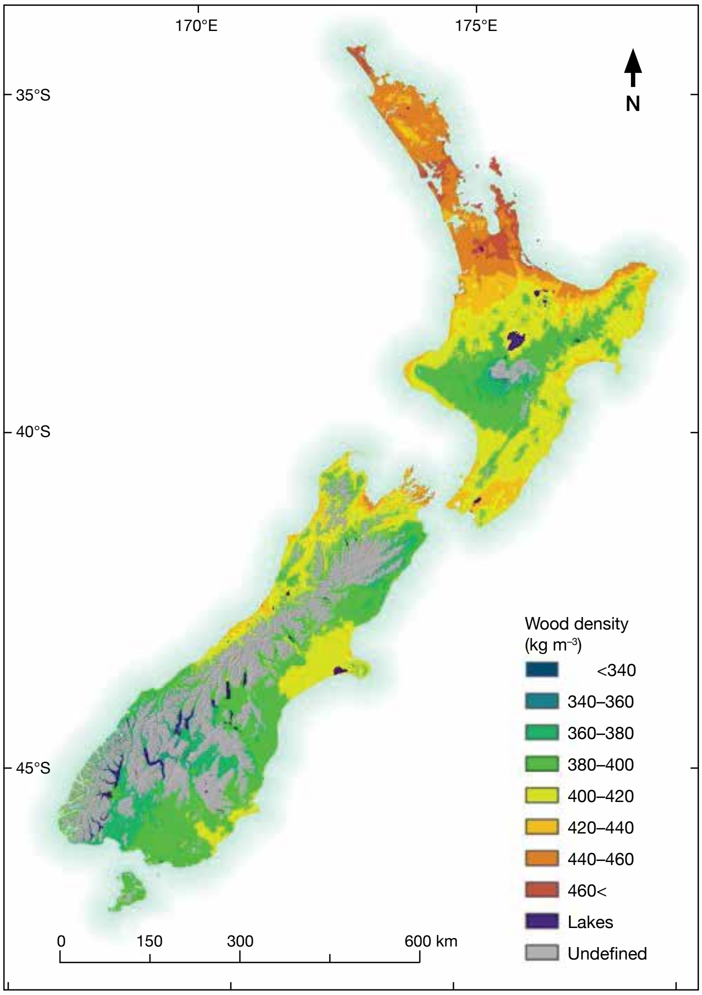

Figure 2: Spatial variation in predicted *Pinus radiata* outer wood density across NZ for 20-year-old trees. Source: Palmer et al., 2011

The stem descriptions were converted to a format that could be used in the techno-economic model. These descriptions included: (a) stem length after breakage; (b) under-bark stem diameters; and (c) wood density. External and internal properties were described in decimetre increments up the stem. Secondary leaders from multi-leader stems were not included in the analyses.

Each stem was bucked into 5.2 m long logs and the average wood density calculated for each log. Logs with an SED less than 150 mm under-bark were excluded from further analyses. Up to seven logs were cut from each stem. Log positions were labelled from 1 up to 7, with log position 1 being at the base of the tree. It was assumed that there was minimal stem curvature in all logs cut.

RTL values were calculated for each log using the techno-economic model. These were sorted into groups by forest stand (StandID), log position and SED class. SED Classes A to I were in bands of 50 mm (e.g. Class A 150–199 mm, Class B 200–249 mm etc to Class I 550–599 mm). In total, 8,271 logs were included in the log dataset.

Statistical analyses

All analyses were undertaken using Statgraphics Plus 5.1 (StatPoint Technologies Inc, VA). A multi-factor analysis of variance (ANOVA) was carried out with RTL value being the dependent variable and StandID, log position and SED class being the factors. Factors were deemed to be statistically significant if the p-values were less than 0.05.

Post-hoc multiple comparisons of RTL values were carried out between sub-groups of log data using Tukey's honestly significant difference (HSD) multiple range tests. Comparisons were deemed to be statistically significantly different if they exceeded tabular values at the alpha = 0.05 level.

Results

Multi-factor ANOVA

Log densities ranged between 310–487 kg/m^3, with an average of 378 kg/m^3. Log SEDs ranged between 150–587 mm, with an average of 289 mm. RTL values ranged between \$81.91–\$222.84/m^3, with an average of \$149.59/m^3.

Table 2: Multi-factor analysis of variance for mill-gate RTL value – Type III sums of squares

Source	Sum of squares	Df	Mean square	F-ratio	P-value
Main effects					
A: StandID	1.40E6	7	200756	1385	0.0000
B: LogPos	3.36E4	6	55957	386	0.0000
C: SEDClass	1.18E6	8	147144	1015	0.0000
Residual	1.20E6	8249	145		
Total corrected	5.62E6	8270			
Note: All F-ratios are based on the residual mean square error.					

The multi-factor ANOVA showed that there were statistically significant differences in RTL values between stands, between log positions within a stem and between log SED classes (Table 2).

RTL values decreased non-linearly with height in the tree (Figure 3). Note that the HSD intervals are wide for log positions 6 and 7 (equivalent to 26–36 m up the stem) since so few logs were included in the data from these positions.

RTL values tended to decrease the further south in the country that the stands were located (Figure 3). The two stands with the highest mean RTL values were in Northland and the two stands with the lowest mean RTL values were in Southland/Otago. The trend closely mirrors the trend in wood density, with density tending to decrease with latitude.

RTL values increased non-linearly with SED class (Figure 3). Not surprisingly, larger logs had higher volume conversion factors, which yielded higher RTL values. Note that the HSD intervals are wide for SED Class I (SEDs from 550–599 mm) since there were so few logs of this class included in the study.

Comparisons of mean RTL values grouped by SED class

To facilitate understanding of the effects of stands and log positions within stems on RTL values, comment will initially focus on one SED Class C (250–299 mm), which contained 1,875 logs. The average SED of all logs included in the study was within this class (i.e. 289 mm). Comment will then be expanded to include other SED classes.

For the same log SED class, there was considerable overlap in the distributions of RTL values for different log positions in stems (as shown by Figure 4), even for a single stand. Similarly, for the same log SED class, there was considerable overlap in the distributions of RTL values between stands for the same log position. Figure 5 shows the distribution of RTL values for log position 3 for the two stands with the smallest and largest mean breast height outer wood densities. The distributions for the other six stands are not plotted, but the peaks of the distribution move to larger RTL values as breast height outer wood densities increase.

In Table 3, log positions within a stand (= row), with the same lowercase letter, are not significantly different from other log positions in the same row. Stands within a log position (= column), with the same uppercase letter, are not significantly different from other stands in the same column.

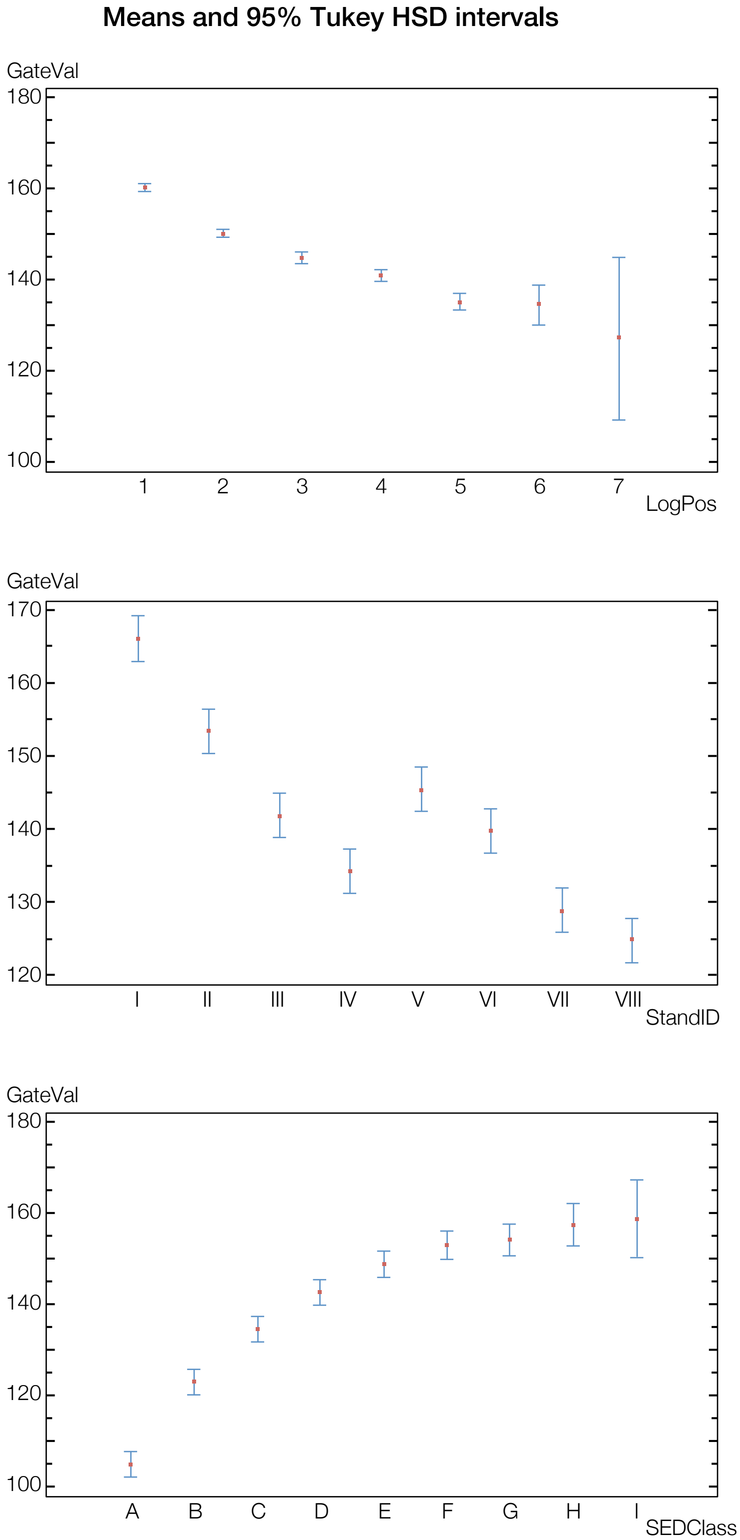

Figure 3: Simple arithmetic means and Tukey's HSD intervals for mill-gate RTL values for three factors: log position up the tree; StandID; and SED class (classes are in 50 mm diameter groupings starting with group A being from 150–199 mm)

For all eight stands, mean RTL values, for SED Class C, decreased as the log position increased up the stem.

Table 3: Comparison of mean RTL values ($/m³) for SED Class C (250–299 mm) based on Tukey's HSD multiple range test (values have been rounded to the nearest $)

Stand	Log position 1	Log position 2	Log position 3	Log position 4
I	$180 a A	$170 b A	$159 c A	$156 c A
II	$166 a B	$158 a B	$146 b B	$142 b B
III	$155 a B, C	$141 b C, D	$134 b, c C	$134 b, c B, C
IV	$145 a D, E	$135 b D, E	$128 c D	$125 c D, E
V	$161 a B	$145 b C	$139 c C	$133 c B, C, D
VI	$150 a C, D	$139 b D	$136 b C	$131 b B, C, D, E
VII	$136 a E, F	$131 a, b F	$126 c D, E	$122 b, c C, D, E
VIII	$133 a F	$127 b E, F	$123 c E	$119 b, c E

For all stands, log position 1 had significantly higher mean RTL values than logs from positions 3 and 4, and for six of the eight stands log position 1 also had significantly higher mean RTL than for log position 2. Logs from positions 3 and 4 always belonged to the same grouping (i.e. there was no statistically significant difference between them). Mean RTL values for log position 2 always sat between RTL values for log positions 1 and 3, but for some stands there was no significant difference between higher or lower log positions.

This trend is similar to the trends for mean wood density for these logs which also decrease with position up the stem (Figure 6).

Comparisons of mean RTL values for given log positions showed that there were also significant differences between some stands (Table 3). Stands I and II (located in Northland) had significantly higher mean RTL values than Stands VII and VIII (located in Southland) for all log positions. Stands from the middle regions (Stands III, IV, V and VI) tended to fit into multiple groupings.

If comparisons are only made between logs from stands in the same region, mean RTL values were significantly different between Stands I and II for all log positions, between Stands III and IV for three of the four log positions, between Stands V and VI for two of the four log positions, and between Stands VII and VIII for none of the four log positions evaluated.

Similar to SED Class C, there was a tendency in the other SED classes for mean RTL value to decrease with log position up the stem. Also, logs within the same diameter classes coming from positions high in the stem had lower, and statistically significant, mean RTL than logs coming from the base of the stem. Logs from intermediate positions were often not significantly different from logs from adjacent positions.

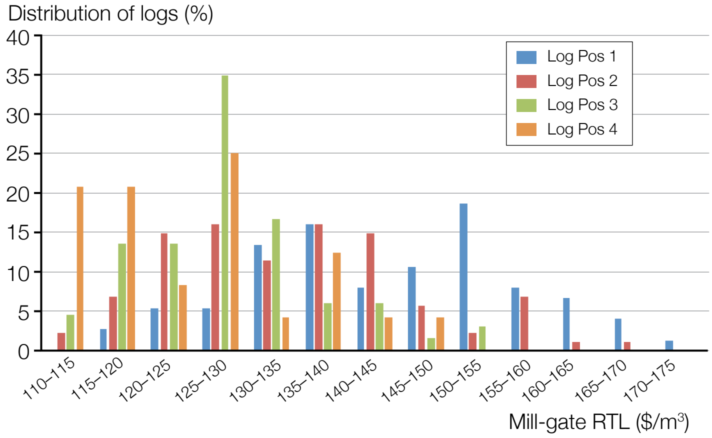

Figure 4: Distribution of logs by RTL values for four log positions and for Stand IV

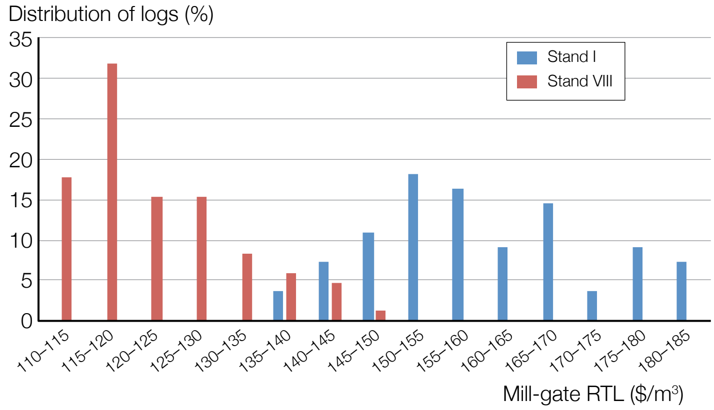

Figure 5: Distribution of logs by RTL values for two stands and for log position 3

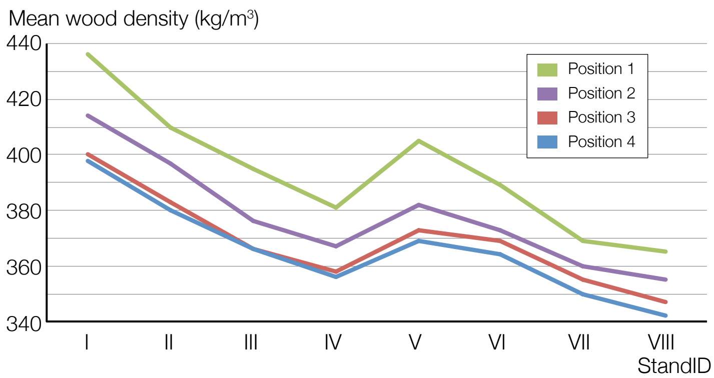

Figure 6: Mean wood density values of logs ranging in SEDs between 250–299 mm for eight stands at different log positions within stems

Relative changes in mean RTL values with log position

As noted above, the mean RTL values tended to decrease with height in the stem within each SED class. On average there were –7%, –11%, –13%, –14% and –18% differences between mean RTL values for log positions 2, 3, 4, 5 and 6, respectively, compared to log position 1 (Figure 7). It should be noted, however, that the relative size of the changes between log positions was neither constant, nor trending in a consistent manner, between SED classes.

Discussion and conclusions

RTL values were based on empirical models of volume conversion factors and structural grade conversion factors that had been developed by the New Zealand Forest Research Institute and WQI Ltd. Volume conversion factors are largely determined by log size (SED) and shape (taper, sweep); large logs having higher conversion factors than small logs. Grade conversion factors are mainly affected by wood properties (e.g. denser logs producing greater proportions of higher strength lumber).

Other studies have reported the impact of the variation in internal wood properties within stands and stems on RTL values. For example, RTL values of Douglas-fir logs in Oregon, destined primarily for lumber and veneer markets, have been shown to increase with increasing wood density (Acuna & Murphy, 2006, 2007) and increasing log stiffness (Amishev & Murphy, 2008, 2009) within stems and between stands.

In the analyses reported herein for radiata pine logs, there was a 174% difference in RTL value between the log with the smallest RTL value ($81.91/m^3) and the log with the largest RTL value ($222.84/m^3). Not unexpectedly, the RTL values were shown to decrease with height up the stem, to increase with increases in log size (= SED class) and to differ between stands.

Log markets pay a premium for log size (SED) in this country, but there is little evidence of a premium being paid for logs with superior internal wood properties within New Zealand or internationally (Murphy & Cown, 2015). The analyses showed, however, that logs within the same size class can have significantly different mean RTL values for wood processors, depending on which stands the logs come from (up to 40% difference) and where in the stem the logs come from (up to 18% difference). The differences are largely due to differences in wood properties.

It should also be noted that the density values for each log used in the analyses were not measured directly, but were first measured on a pre-harvest inventory sample of stems (or predicted) at breast height and then extrapolated to other stems within the stand and to other heights in the stems. It has been suggested by Scandinavian researchers that wood properties models similar to those used in our study could be used in bucking computers on harvesting machines to allocate logs to the most appropriate use (Wilhelmsson et al., 2002). Knowing the stand from which the logs came from and the position within the stem is an essential requirement for making the best use of these models. An individual log ID, attached at the time of processing stems into logs, would help to ensure that this information remains linked to the log.

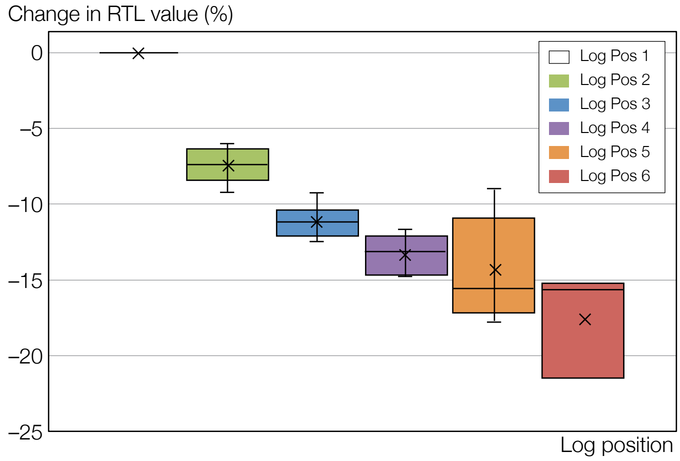

Figure 7: Box and whisker chart of change in mean RTL value, relative to log position 1, for all stands combined and for SED Classes A to F. The variation within a log position is due to differences between SED classes

Even if individual log ID's were not attached to each log, given that the logs in position 1 had a better RTL value than those in other positions across most SED classes, there could be value in marking these with the paint applicator on a processor head. While differentiating logs from the base of a stem from other log positions, this would not differentiate logs from other stands within the same SED class.

There are some limitations to this study. The results are based on volume conversion factors obtained from mill studies that are at least 20 years old and structural grade conversion factors that were developed from mill studies more than 10 years ago. The conversion factors may have improved with time with the implication that RTL values may be under-estimated. Also, the lumber prices and mill costs used in the analyses were based on averages that are at least five years old and may not relate to current market conditions or any specific mill. Nevertheless, the relative size of the differences in mean RTL values are not small and should be of some interest and relevance to forest owners and wood processors.

In conclusion, this paper has demonstrated that, for radiata pine logs of the same SED, there are differences in mean RTL due to differences in wood density arising from the position on the stem and the stand from which logs are cut. If the differences are considered by log buyers and sellers to be large enough to exploit, individual log ID tagging could provide an opportunity for forest owners and wood processors to segregate logs based on wood property differences and to potentially share improvements in value recovery.

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