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Sawn timber grade recovery from a planted coast redwood stand growing in New Zealand

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Abstract

Background: Timber from old-growth stands of coast redwood (*Sequoia sempervirens* (D.Don) Endl.) is dimensionally stable, resistant to surface checking and splitting, and has been widely used for outdoor purposes such as decking and cladding. Restrictions on the supply of redwood timber from Californian stands have increased the focus on timber from plantations grown elsewhere in comparatively short rotations. Little is known about the quality of timber produced from plantations of redwood in New Zealand.

Methods: In this study trees from a 38-year-old pruned stand in Mangatu Forest near Gisborne, New Zealand, selected to cover the range of stem diameters present, were cross-cut into logs. Each log was then sawn into boards and each board was graded according to a simplified United States redwood grading system.

Results: Total timber volume (50 logs) was 16.2 m^3, valued at USD 7,835 (2008 prices). This was less than might be expected in a well-managed stand. The 13 pruned logs accounted for 38% of the total volume recovered and 50% the total financial value of the timber. Pruned log quality assessed according to a pruned log index (PLI) was low, due to untimely pruning and the presence of epicormic shoots. Only 12% of the timber was graded clear and 32% of this came from pruned logs. Despite low PLI scores, the relationships between PLI, proportion of clear timber and pruned log value were reasonably strong.

Conclusions: Recoveries from individual stems were variable. The most important determinants of log value were log size, which affected timber recovery; pruning quality, which governed the volume of clear wood; the proportion of heartwood, (valued for durability and appearance); and to a lesser extent, mid-stem branch vitality. High incidence of dead (bark-encased) knots in most of the unpruned logs contributed to the poor timber grade recovery results. Other defects (insect tunnels, rot and traumatic resin pockets) were associated with a 7% reduction in financial value. Accurate prediction of the pattern of distribution of heartwood inside a redwood log could play a major role in maximising the value of recovered timber.

Keywords: *Sequoia sempervirens*; Wood properties; Pruned log quality; Timber grades

Background

California coast redwood (*Sequoia sempervirens* (D.Don) Endl.) is a native of the fog belt that extends from southwest Oregon to central California on the Pacific coast of North America. Some specimens are among the tallest living plants in the world, reaching more than 100 m. "Old growth" redwood timber has been highly prized for several unique features. The sapwood is white, but the stem consists mainly of dark red heartwood with very straight grain, low shrinkage, high dimensional stability and good resistance to warping. As one of the most dimensionally stable of the western softwoods, redwood is resistant to checking and splitting, and is therefore less affected by weather than most softwood species. It has been widely used for outdoor decorative purposes (decking and cladding). All heartwood timber grades are considered to be more durable and insect resistant than heartwood of other softwood species, yet the wood is lightweight and exceptionally stable. According to reports from the USDA Forest Products Laboratory (USDA 1999), old-growth redwood is less subject to dimensional shrinkage than other common domestic softwoods.

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Utilisation of the North American redwood resource is limited by legislation governing environmental concerns and sustainable forest management practice. As a consequence production from second- and third-crop stands is likely to continue to decrease (Stuart 2007). The US supply of old growth timber is now a very small part of the market. Most of the supply comes from second- and third-growth stands less than 100 years old where wood characteristics are different. In particular, the heartwood from these stands has only low to moderate decay resistance (USDA 1999). The timber is used mainly in building and landscaping where appearance, durability and stability are important (decks, fences, outdoor furniture, weatherboards, window sashes, doors, blinds and interior trim).

In New Zealand, redwood has been a frequent feature of the landscape since the nineteenth century. It is found in small woodlots and ornamental plantings throughout the country (Knowles and Miller 1993). Some iconic remnants of the early plantings, such as the Redwood Grove in Rotorua, prove that this species can grow well when correctly sited. In the first half of the 20th Century, the New Zealand Forest Service planted many exotic temperate species throughout the country, and included redwood because of the high value of the Californian old-growth forests. Many plantings were unsuccessful for a variety of reasons, and the quality of the timber was disappointing when compared with US old-growth material (Brown I 2007). Redwood was later found to have more specific site requirements than other softwoods, notably radiata pine (*Pinus radiata* D. Don). When plantings happen to be located on sites suitable for redwood, it can be highly productive and produce impressive redwood stands (Libby W.2007).

In the last 20 years, there has been a renewed interest in redwood as a commercial forest species. This interest was largely driven by the efforts of Bill Libby, then Professor of Forestry at the University of California at Berkeley, USA (Libby 1993; Brown et al. 2008a). A better understanding of siting for redwood has led to the establishment of young stands with good growth rates, and in some places able to rival the growth rate of radiata pine (Brown, Low, McConnochie et al. 2008b; Ripley 2009). It has been demonstrated that proper establishment practices and weed control after planting can lead to high survivability and good growth rates (Bowles 1980; Nicholas and Rapley 2008). Some companies have planted clonal stock of redwood designed for relatively short rotations of approximately 35 years (Knowles and Miller 1993; Rydelius 2007). Variability in survival and growth rates has led interested individuals to establish small trials, many of them containing clonal material originating in California (Saunders and McConnochie 2007; Rydelius 2007). However, these trials are still young and have not yet yielded information apart from initial survival and growth rates.

The most important criterion for a successful planted forestry species is the acceptability of products in both domestic and export markets. An important aspect of the conversion of redwood logs to sawn timber is the recovery of the heartwood prized for its stability, colour and durability. For most timber grades, a premium price is paid for a high percentage of heartwood. For example, Clear All Heart and Heart B grade boards must be 100% heartwood, and for all other grades the heartwood requirement is at least 90%.

Little work has been done on the wood properties and performance of New Zealand-grown redwood. Acknowledged gaps in information about wood density, stability and durability (Poole 2007; Cooke and Satchell 2007) could affect export markets. Some observers rightly caution that market requirements for both domestic and export purposes should be considered before any long-term commitment is made to fast-growing redwood (Cornell 2007).

Most of the New Zealand redwood stands that demonstrate good growth characteristics and are old enough to assess wood properties come from older stands that were planted before the 1980s. Thus, these stands were grown from unimproved genetic stock and were not subject to modern silviculture. As such, they cannot be expected to display features associated with current redwood management practices. In order to establish "baseline" information about the wood properties of redwood in New Zealand, an older stand that is the most representative of modern redwood management was selected for documentation of its log and timber properties. Interest centred on identification of characteristics that could be used for inclusion in breeding programmes and also on better understanding of the effects of silviculture on redwood in New Zealand. Selected wood properties of a log sample taken from this stand have described (Cown and McKiney 2009). This study contains details of log conversion and timber grade recovery, and offers comments on silvicultural practice likely to maximise value. It is not a full economic analysis of stand volume assessment, harvesting costs, etc., but follows the design of other sawing studies carried out at Scion (Park 1989, 1995). The overall objectives were: (1) to document the influence of silviculture on wood quality and timber grade recovery; and (2) to identify tree and log characteristics that govern the financial value of redwood timber in New Zealand.

Methods

The stand selected for study was a small block (1.4 ha) of *S. sempervirens* located near Gisborne in Compartment 11, Mangatu Forest (Latitude 38°16'28"S; Longitude 177° 58'42"E). The trees were planted in 1970 at an initial stand density of 3086 stems ha^{-1}. They were pruned four times to a height of approximately 5.8 metres, and thinned twice to a residual stand density of approximately 398 stems ha^{-1} (Table 1). Harvesting in 2008 and sawing were described previously (Silcock 2008).

Tree selection and pre-cutting measurements

In order to show the effects of tree size and silvicultural treatment on timber quality, 13 trees representing the diameter range of all trees in the stand were selected and felled. Diameter over bark at breast height of 1.4 m (DBHOB), total height, pruned height and height to the base of the green crown were measured on each tree. Branches above the pruned section of each stem were categorised as live, small dead, or large dead. Increment cores 50 mm long x 5 mm diameter were taken at breast height for assessment of basic wood density (Cown and McKiney 2009). After felling, cross-sectional diameter measurements over- and under-bark were made at the base of the stem, at breast height, and at 3 m intervals up the stem. Branch condition up to a small end diameter (SED) of 20 cm was categorised and noted in the database as pruned, epicormic, live, small dead, or large dead.

Log measurements

The 13 stems were cut into 50 logs, including 13 pruned logs. Length of the pruned log varied slightly to maximise clear wood recovery. Allowing for discs to be taken for wood property measurements, pruned logs were cut into lengths that were multiples of 0.3 m up to a maximum of 5.5 m. Upper unpruned logs were cross-cut to a fixed length of 4.9 m. Top logs were cut to an SED of 20 cm and divided into multiples of 0.3 m from the shortest merchantable length of 3.1 m. Wood discs, 50 mm thick, were taken from both ends of each log for determination of heartwood content, density, stiffness and dimensional shrinkage in sections representing five growth rings (Cown and McKiney 2009).

Log profiles (measured according to the method described by (Park 1989) for pruned log index studies) were used to calculate log volumes and sawn timber conversion yields. For pruned logs the 3-dimensional log profiles and defect information were used to calculate a pruned log index (PLI), used as a measure of basic clearwood potential excluding randomly occurring defects such as resin pockets (Anderson 1961):

$$\mathrm{PLI} = ((\mathrm{D}_{1.3}\text{-}\mathrm{DC})/10)^{0.5} * (\mathrm{D}_{1.3}/\mathrm{DC})^{0.2} * (\mathrm{C}_{\mathrm{vol}}/\mathrm{L}_{\mathrm{vol}})^{1.6} \quad (1)$$

Where:
$D_{1.3}$ = diameter of the log at 1.3 m (mm);
DC = defect core diameter (mm);
C_{vol} = timber volume (m^3);
L_{vol} = log volume (m^3).

Branch diameter measurements for each log quarter were determined in each of the unpruned logs. The diameter of heartwood in two orthogonal directions was measured at both ends of each log. The offset of the pith from the geometric centre of the log at both the small and large ends was also measured.

Sawing and grading of timber

The logs were sawn at the Waiariki Training Centre, Rotorua. The objective for sawing pruned logs was maximum clear-wood recovery. The maximum extent of knots and occlusion scars from the pith were recorded in order to determine the size of the defect core (DC) and hence the PLI of the log (Park 1989). When sawing pruned logs, boards with a nominal thickness of 25 mm were removed until the first defects were visible; thereafter 45 mm boards were sawn. Sapwood of unpruned logs was removed by cutting 25 mm boards. Boards of 45 mm thickness were then cut, maximising board width from the heartwood zone. Minimum recovered dimensions were 1800 x 100 x 25 mm. A total of 772 boards were obtained, with 303 boards from pruned logs.

The length, width, thickness, percentage of visible rot, percentage of heartwood, size, location and condition of knots (live, dead, rotten), number of resin pockets and clear-cuttings dimensions were measured and recorded for each board. All timber from the pruned logs was reconstructed into the logs and the locations of defects (i.e. length along the board, knot depth and occlusion depth) noted. The presence or absence of heartwood was recorded at 0.5 m intervals along the board. Board dimensions and saw kerf thickness measurements were converted into x, y and z coordinates (z being the axial distance along the log) so that maps could be created at a later date. This information would also be useful for future construction of virtual pruned logs in a sawing simulator. A sawn timber conversion percentage (proportion of sawn timber volume to log volume) was calculated for each log and mathematical relationships were defined for SED, Conversion Potential (CP) factor,

Table 1 Silvicultural history of the redwood stand

Activity	Age (Year)	Description
Pruning	9 (1979)	Fixed lift to 2.2 m
Thinning	9 (1979)	To waste to 800 stems ha^{-1}
Pruning	10(1980)	Fixed lift to 4.0 m
Pruning	12(1982)	Fixed lift to 5.8 m
Thinning	12(1982)	To waste to 398 stems ha^{-1}
Pruning	15(1985)	To 5.8 m

Table 2 (A) Appearance grades (25 mm) and (B) construction grades (50 mm +)

Grade	Sapwood	Pockets	Wane	Checks/ Birdseye	Shake	Stain	Rot	Holes	Sound knots (mm or area)				Sound occlusion
A													
									Face	50-150 mm	200-250 mm	300 mm	
Clear All Heart (CH)	No	Nil	Nil	Nil		Medium	Nil	Nil		Nil	Nil	Nil	Nil
Clear Common (CC)	Yes	2, 3x25mm	10% W 25% T	Yes		Medium	Nil	Nil		2, 19mm	2, 19mm	2, 19mm	Back 2 small
Heart B (HB)	No	2 small	10% W 25% T	Yes		Medium	Nil	3 mm, some pin		33% area	50mm	63mm	Back only
B Common (BC)	Yes	2 small	10% W 25% T	Yes		Medium	Nil	3 mm, some pin		33% area	50mm	63mm	Back only
Merchantable Heart (MH)	10% of 1 face	Yes	50% T 25% W	Yes		Medium	2 ½ knot	As knot size	<50	60% area	40% area	125mm	Yes
Merchantable Common (MC)	10% of 1 face	Yes	50% T 25% W	Yes		Medium	2 ½ knot	As knot size	<50	60% area	40% area	125mm	Yes
B													
								75-150; 200-300 widths		50-150 mm	200-250 mm	300 mm	
Construction Heart (ConH)	10% of 1 face	4 medium	13mm 10%w 25%T	Yes	2mm 25%L	Medium	Nil	19mm 25mm	50mm 75mm	½ area	1/3 area	1/3 area	Yes
Construction Common (ConC)	Yes												Yes
Merchantable Heart (MH)	10% of 1 face	Yes	50% T 25% W	Yes		Medium	2 ½ knot	As knot size	<50mm	60% area	40% area	125mm	Yes
Merchantable Common (MC)	10% of 1 face	Yes	50% T 25% W	Yes		Medium	2 ½ knot	As knot size	<50mm	60%	40%	125mm	Yes

Face = Visible "best" face.
W = Width; T = Thickness.
Source: Redwood Inspection Service (http://www.redwoodinspection.com/publications.htm).

PLI, heartwood content and percentage of dead and rotten branches.

The timber was graded according to criteria defined by the Redwood Inspection Service (RIS - http://www.redwoodinspection.com/grades.html), an organisation exclusively authorised by the American Lumber Standard Committee, Inc. to formulate grading rules for redwood timber. The rules were established in accordance with Product Standard 20–94, the *American Softwood Standard*, issued by the U.S. Department of Commerce. Since more than 30 RIS grades are used for redwood timber, a subset of ten grades from the General Purpose Group (Table 2)

Table 3 Grading rules and corresponding timber prices (for the second quarter of 2008) used to determine the financial value of the sampled redwood trees

Grade	Proportion of heartwood (%)	Live branches	Dead branches	Rotten branches	Rot	Price (USD m^{-3})[1]
Clear All Heart (CH)	100	Nil	Nil	Nil	Nil	1,484
Clear Common (CC)	< 100	Nil	Nil	Nil	Nil	1,060
Heart B (HB)	100	Allow (50 mm)	Nil	Nil	Nil	572
B Common (BC)	< 100	Allow (50 mm)	Nil	Nil	Nil	572
Construction Heart (ConH)	> 90	Allowed	Allowed	Nil	Nil	477
Construction Common (ConC)	< 90	Allowed	Allowed	Nil	Nil	373
Merchantable Heart (MH)[2]	>90	Allowed	Allowed	Allowed	Allowed	233
Merchantable Common (MC)[2]	< 90	Allowed	Allowed	Allowed	Allowed	180

[1] price data obtained from anonymous commercial sources.
[2] combined construction and appearance grades.

Table 4 Pre-felling measurements of the sampled redwood trees

Tree No.	DBH (mm)	Tree height (m)	Pruned stem height (m)	Height to crown (m)	Branch condition[1]	Outerwood density (kg m^{-3})
1	511	29.4	5.2	5.2	G	274
2	400	35.2	6	24.7	G	385
3	380	31.4	6.5	6.5	G	420
4	385	31	4.5	24.5	S	360
5	583	31.8	6.6	25	S	405
6	770	41.1	6.1	23.8	S	335
7	602	40.4	6.8	25.8	S	345
8	680	32.6	5.2	15.2	G	305
9	603	38	6.5	22.3	L	347
10	810	35.5	7.1		L	341
11	565	32.7	6.5	19.7	L	333
12	540	40	6.1	25	S	382
13*	842				S	299
Mean	**590**	**34.9**	**6.2**	**19.8**		**348**
Min.	380	29.4	5.2	5.2		274
Max.	842	41.1	7.1	25.8		420

[1] *G* = Live branches; *S* = Small dead branches; *L* =Large dead branches.
*Data for tree 13 was lost due to stem breakage when felling.

together with a simplified set of grading rules (Table 3) was used for this purpose.

Computerised re-grading of the timber from both pruned and unpruned logs was carried out in order to simulate the effects of silvicultural practice on defect core size and the presence of knots. It was assumed that the number of branch and occlusion defects found in the logs was due to late pruning and tolerance of an epicormic shoots, which would not be present in a stand managed for clearwood. For pruned logs the regrading scenario simulated depicting timely pruning to a defect core diameter of 185 mm and removal of epicormic shoots. For the unpruned logs, the re-grading scenario simulated a “brashing” regime in which any dead or dying branches in the lower crown were removed in order to avoid development of dead, bark-encased and rotten knots. In reality this could be achieved through high pruning in mid-rotation or timely production thinning designed for maintenance of a longer live crown. It was assumed that no dead or rotten branches would be in the lower crown zone (second and third logs).

Prediction of financial value of logs and timber

For the empirical and the simulated silvicultural scenario, per hectare grade recoveries were estimated by multiplying log volume ha^{-1} for each diameter class as predicted by the redwood growth model by the appropriate sawn timber conversion percentage and grade out-turn distribution. The value of the logs was calculated from sawn timber by multiplying the volume of each grade by the price paid for that grade during the second quarter of 2008. A list of market prices for various grades of redwood timber is shown in Table 3. Price per thousand board feet was converted to price per cubic metre using a factor of 0.424. Because the Californian market dominates global redwood timber sales and currency rates are volatile, all prices and values in this

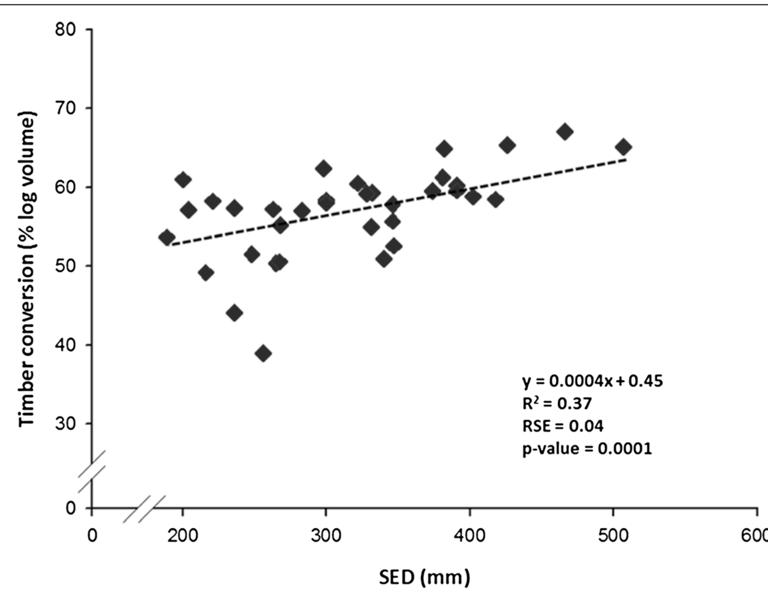

Figure 1 Relationship between small end diameter (SED mm) of unpruned redwood logs and the proportion of sawn timber volume recovered from each log (timber volume %).

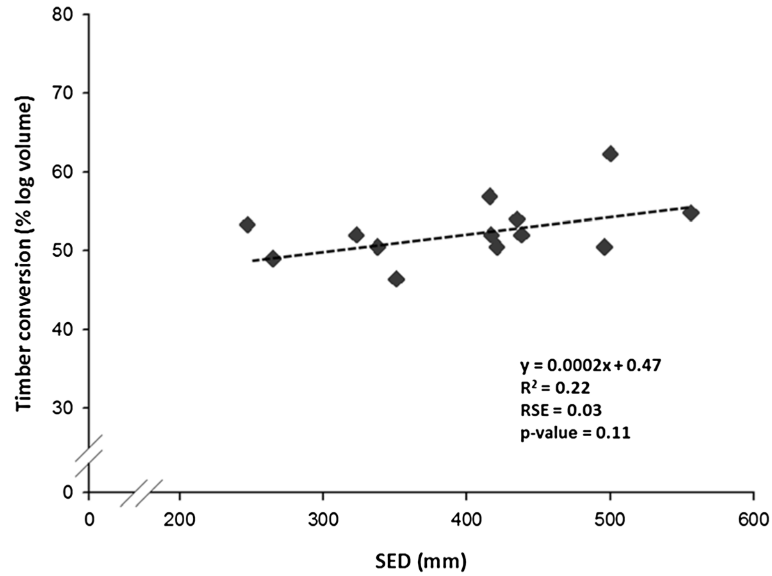

Figure 2 **Relationship between small end diameter (SED mm) of pruned redwood logs and the proportion of sawn timber volume recovered from each log (timber volume %).**

report are given in US dollars. Regression analysis was used to examine the relationships between stem and log variables, the extent of timber recovery and its financial value.

Results and discussion

Empirical Data

Stem properties

Most of the trees in the stand had a large number of dead branches in the mid-portion of the stem. Table 4 shows that the DBH of the 13 sample trees ranged between 380 and 842 mm (mean 590mm) and height between 29.4 and 41.1 m (mean 34.9 m). The trees had a high heartwood content (mean 54%; range 44 - 66%) and an average whole-stem wood density of 323 kg m^{-3}; range 262–380 kg m^{-3}. Between-tree variability was high, as found in other New Zealand studies (Cown 2008), indicating that some potential exists for improvement of wood properties through selective breeding.

Log properties and timber conversion relationships

At least three logs were cut from each stem, with some stems yielding up to five logs. A total of 50 logs were obtained. Dead and rotten branches were present in some of the upper logs. Total log volume for all 13 trees was 28.09 m^3, yielding 16.02 m^3 of sawn timber. The average sawn timber conversion rate for unpruned logs to sawn timber (57.6%) was moderately but highly significantly related to SED ($R^2 = 0.37$, $p < 0.0001$; Figure 1). Two logs (14C and 14D) were omitted from further

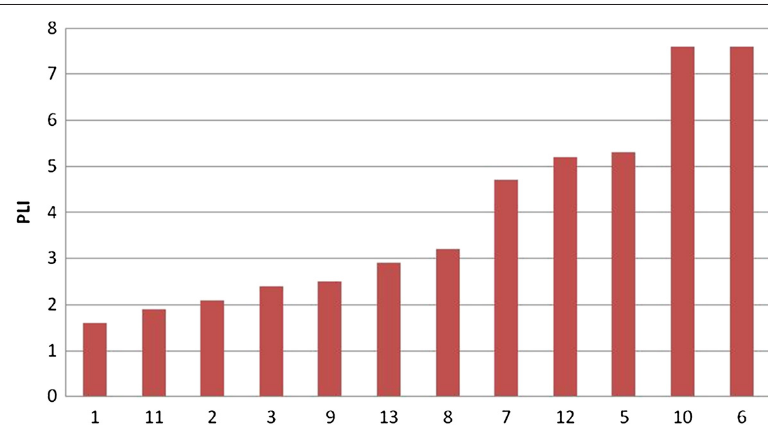

Figure 3 **Ranking of sample redwood trees according to pruned log index (PLI) calculated for the bottom pruned log.**

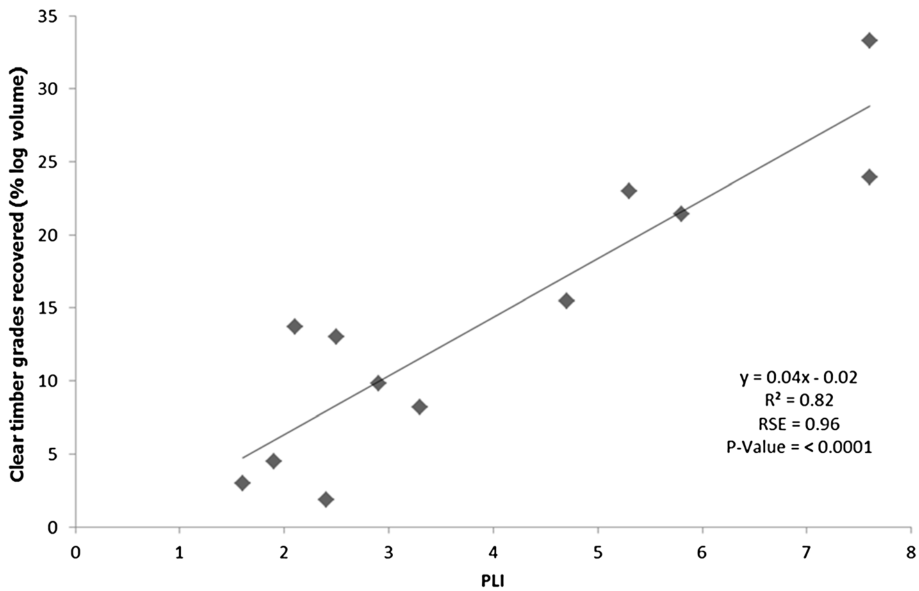

Figure 4 **Relationship between pruned log index (PLI) of redwood and percentage of the volume of clear grades of timber (Clear All Heart and Clear Common grades) recovered from each log.**

analysis because of anomalous conversion results (39% and 79% respectively), which probably arose from incorrect labelling of boards. Out of the 50 logs processed, 13 were pruned. The relationship between actual sawn timber conversion rate and SED for the pruned logs was not statistically significant (Figure 2). A PLI could not be calculated for Tree 4 due to the short length (3.7 m) of the pruned log. For the remaining sample trees, PLI values ranged between 1.6 and 7.6 (Figure 3). Application of the PLI requirements for radiata pine (> 6.0; for "good" logs (Park 1989) would have allowed only two logs to be classed as satisfactory. There was a strong positive relationship between the proportion of recovered clear grades of timber (Clear All Heart and Clear Common) and PLI (R^2 = 82%; Figure 4). Significant correlation between these two variables has also been observed in *Pinus radiata* (Park 1995, 1989).

Knots and epicormic shoots were the main features influencing the size of the defect core and hence the PLI. For the 13 trees sampled, the mean occlusion width (radial distance for complete knot occlusion) was 7.7 mm; the mean defect core diameter 305 mm. Defect core diameter averaged 60% of DBH (Table 5). Size of the defect core (often expressed as diameter over occlusion or DOO) is known to be influenced by branch collar geometry, bark thickness, and growth rate at time of pruning as well as silvicultural treatment. Resin pockets were observed in 5% of the boards.

Modern silvicultural regimes for redwood are based on the preliminary results of a pruning study of redwood at Tutira, Hawke's Bay (Scion, unpublished data). Results showed that medium intensity pruning to 10.5 mm stem diameter resulted in a mean DOO of 180 mm. The higher average DOO (305 mm) in Mangatu trees had a large negative effect on the amount of clear heartwood timber produced and is much higher than the radiata industry DOO target of 180 mm. The Tutira trial demonstrated that application of modern silviculture to

Table 5 Defect core diameter (DOO) and occlusion rate and heartwood percentage in individual redwood butt logs

Tree No.	Mean defect core diameter (mm)	Defect core/DBH (%)	Mean occlusion width (mm)	Heartwood (Rings)	Heartwood (%)
1	301	59	10	15	52
2	238	59	5	17	53
3	211	56	7	15	54
4[1]			6	15	54
5	255	44	8	17	55
6	317	54	8	21	61
7	321	53	6	20	48
8	343	87	6	25	63
9	372	94	6	22	56
10	313	52	9	23	64
11	307	54	9	15	52
12	318	50	7	24	61
13	358	57	8	24	67
Mean	**305**	**60**	**7**	**19.5**	**57**

[1] No defect core data collected for tree 4 due to short log length.

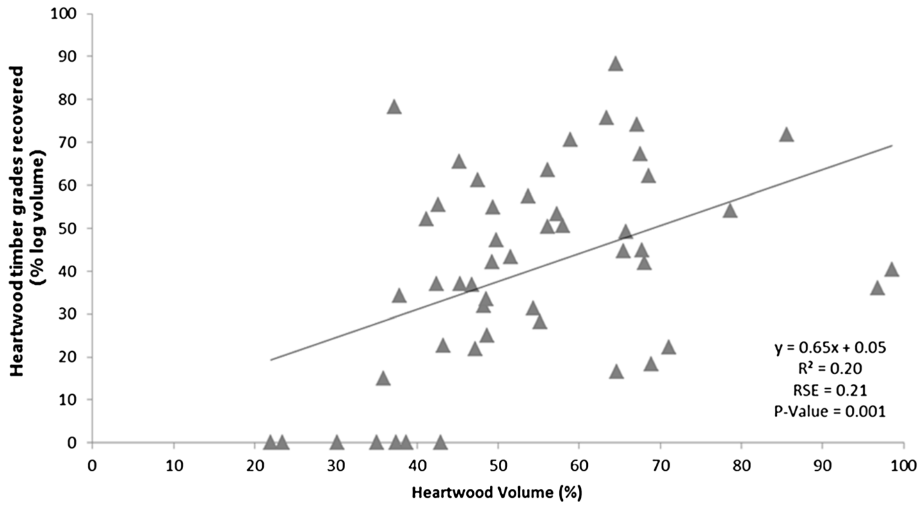

Figure 5 Relationship between estimated heartwood percentage in redwood logs and the percentage of heartwood-grade timber recovered.

plantation redwood can achieve DOO values closer to the radiata industry standard and provided a basis for the timber re-grading simulation.

There was only a weak relationship between the percentage of heartwood in the logs and the proportion of timber graded as heartwood (R^2 = 0.20, p = 0.001; Figure 5). The heartwood content was difficult to determine from log end measurements, and reconstruction of the pruned logs showed that heartwood did not form a perfect cylinder.

Timber grade recovery

Of the possible grades used in this study (Table 2), the predominant grade recovered both from pruned logs and unpruned logs was the Construction Common grade, followed by the Construction Heart grade (Figure 6). Unpruned logs contained no Clear Common or Clear All Heart grades. 12% of the timber from all logs was graded as clear grades of timber while pruned logs yielded a significant proportion (38%) of Clear Common grade timber, but only a small amount of the

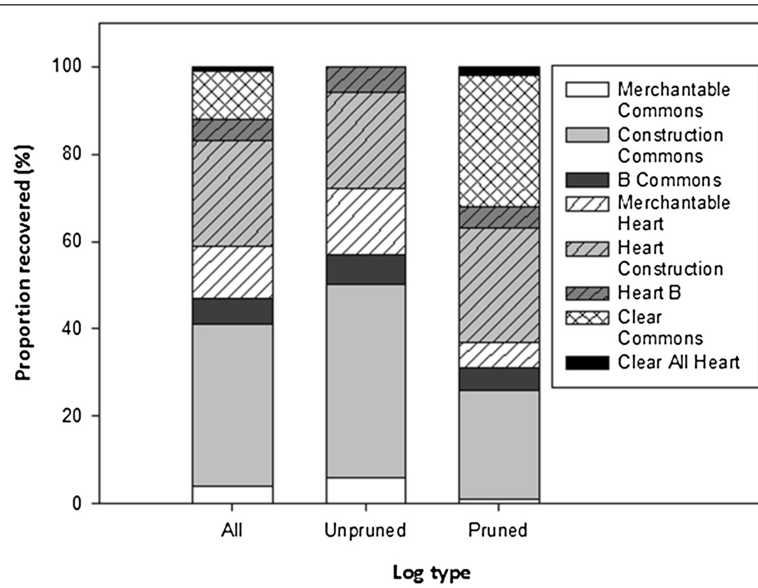

Figure 6 Proportion of sawn timber recovered for each grade by redwood log classification.

Figure 7 **Examples of staining, rot and insect damage observed in redwood boards during timber grading.**

more valuable grade Clear All Heart. It is possible that appropriate docking and edging routines for the boards would increase the proportion of Clear All Heart grade by transfer of volume from less valuable grades.

Epicormic shoots arise from buds that otherwise remain suppressed in the phloem. Rapid changes in light level, temperature, nutrient availability or moisture e.g. after heavy thinning or severe pruning, can induce epicormic shoot growth. Epicormics cause a "birdseye" effect in timber and have the potential to develop into full sized branches, counteracting any pruning investment by downgrading potential clearwood. In this study, epicormic shoots were visible at the de-barked surfaces of two butt logs. Further signs were observed on the boards of a third butt log during timber grading. Clear All Heart timber with birdseye was downgraded according to the size and incidence of the defect.

The proportions of dead and decayed knots found in stem timber associated with specific branching categories were: live branches 28%; small dead branches 40%; large dead branches 25%. Staining, rot, resin pockets and insect damage (Figure 7) were present to some degree in timber from all log classes. Of the 772 boards, 102 (13% by piece count and 16% by volume) had some heart rot. Insect damage was far less common and was only recorded on 29 boards derived from 3 trees. Damage caused by boring insects was attributed to the native longhorn borer or huhu beetle (*Prionoplus reticularis*) and a New Zealand drywood termite (*Kaoltermes brouni*), both believed to have entered standing trees through dead/rotten branches. Resin pockets were detected in 43 boards (6%). These were often quite large and contained highly viscous resin. There was considerable between-tree variation in pocket frequency (0–20 per board). Resin pockets were associated with all log height classes.

Financial value of logs

Although the sampling method used in this study did not allow full economic analysis at stand level, some features can be reported. The total gross value of all logs from the 13 trees was USD 7,835 (USD 484 per m^3 of recovered timber). Pruned logs accounted for 50% of this amount although they contained only 38% of the total volume produced.

A number of regression models were tested to explore the relationships between stem and log variables, the extent of timber recovery and its financial value. The single most important determinant of the value of both pruned and un-pruned logs was log SED, contributing 43% of the variation in pruned log value (Table 6). This variable reflected the fact that an increased volume of larger diameter logs will increase the proportion of the log that can be converted into sawn timber (Figure 2).

In addition to log SED, the effect of sweep, defect core size and percentage of heartwood SED were tested for pruned logs. Somewhat unexpectedly, none of these three additional parameters had a significant effect on pruned log value after log SED was taken into account (Table 6). This lack of effect was considered to be due to poor-quality pruning, which resulted in the absence of logs with PLI greater than 7.6 and a low overall out-turn of high-value clear timber grades. Despite the lack of significance of defect core size in the model, value can be gained by pruning redwood trees.

Table 6 Statistics for the multiple regression models used to calculate the value of pruned and unpruned redwood logs

Model component(s)	R^2	RSE	F ratio	p-[1]	t	p
Pruned logs						
SED only	0.43	64	7.4	0.021	2.72	0.021*
SED and Defect Core	0.56	59	5.73	0.025	−1.66	0.131 n.s
SED and Sweep	0.67	54	5.44	0.025	−1.64	0.139 n.s
SED and % Heartwood	0.67	57	3.70	0.632	−0.41	0.696 n.s
Unpruned logs						
SED only	0.18	39	7.796	0.008	2.792	0.008**
SED + % Rot	0.45	31	15.77	<0.001	−4.426	<0.001**

** Highly significant.
* Significant.
n.s. Not Significant.
[1] Test of significance relates to a model containing only this component.

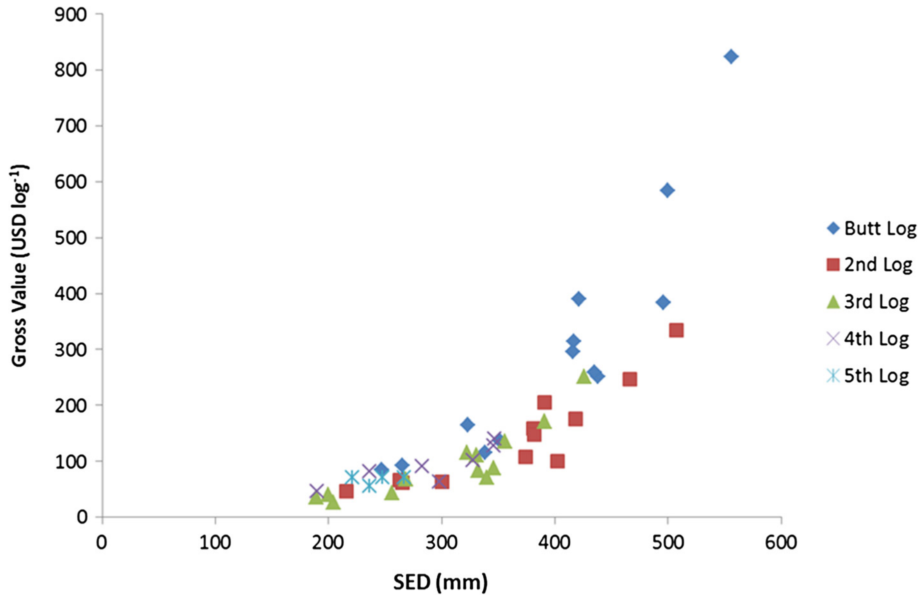

Figure 8 Relationship between log small end diameter (SED mm) and gross financial value of pruned (butt log) and unpruned (2nd – 5th log) logs by segment.

In unpruned logs, the percentage of rot was a major determinant of gross value, (Table 6). Grade return for unpruned logs with or without rot in this study showed a difference in gross value of 7%. It is surmised that, as in the US, the ingress of decay fungi such as *Poria* spp. and insects is a result of physical damage to the stems (Kimmey 1958).

The relationship between log SED and the gross financial value of all study logs is shown in Figure 8.

Timber re-grading using computer simulations

Computer re-grading of the prune log (virtual removal of branches or occlusion defects outside a 185 mm defect core) had a negligible effect on grade recovery from the butt logs. This resulted in re-grading of the 303 boards from the pruned logs (3%). Boards were re-graded from B Common, Construction Common or Construction Heart grades to either Clear All Heart or Clear Common grades (Table 7).

Computer re-grading of the unpruned logs removed of all the dead and rotten knots from second and third logs (simulated "brashing"). The butt log timber grades for this scenario were from the computer re-graded prune log (above). Brashing the second and third logs resulted in a substantial shift in volumes of sawn timber calculated on a stand area basis from the four lowest value grades (Construction Common, Construction Heart, Merchantable Common and Merchantable Heart) to four highest value grades (Heart B, B Common, Clear Common or Clear All Heart) (33% of all pieces, Table 7). Approximately 10% of boards were re-graded to Clear All Heart and Clear Common, the greatest shift being from Merchantable and Construction to B grades.

Table 7 Predicted timber grade percentage per hectare in relation to silviculture

Data Source	Timber volume (m^3 ha^{-1}) and overall percentage yield by grade							
	Clear all heart	Clear common	Heart B	B common	Construction heart	Construction common	Merchantable heart	Merchantable common
Actual pruning	6.8	98.4	29.9	33.2	109.4	260.5	66.2	22.8
%	1	16	5	5	17	42	11	4
Timely pruning	7.4	102.6	29.9	30.5	109.1	258.7	66.2	22.8
%	1	16	5	5	17	42	11	4
Brashing	7.9	138.3	93.9	98.4	76.6	158.3	34.1	19.6
%	1	22	15	16	12	25	5	3

All three scenarios assume a stand density of approximately 400 stems ha^{-1} harvested at age 38.

The study met its objectives by measuring the variation and quantifying the impacts of stem variables on timber grade recovery and crop value in a reasonably mature managed redwood stand. In particular, a revaluation of the logs on the basis of computer re-grading indicated that the value of both pruned and unpruned logs would have been greater if both pruning and removal of epicormics and suppressed branches ("brashing") in the second log had been carried out in a timely manner.

As data for sawn pruned redwood logs accumulates, an index could be developed to include the proportion of heartwood. This would be more informative than the simple PLI used in this study.

Summary and conclusions

The results of this preliminary study on a small sample of trees indicate that the value recovery from individual logs was highly variable. The most important factors determining economic value of redwood trees are: log size (SED); pruning (pruned log PLI); and heartwood content. The amount of rot and insect damage (permitted only in merchantable timber grades) affects the financial value both pruned and unpruned logs (7% in this case). Decrease in financial value due to the presence of dead branches (decayed knots) was less obvious than expected.

The relationship between PLI and the percentage of clear timber was reasonably strong, therefore the PLI could be considered to be a good measure of pruned log quality in redwood as it is in radiata pine. The relationship between log SED and pruned log value was also reasonably strong. Despite the low yield of high-value grades, pruned logs accounted for more value than the unpruned logs. Large DOO values and the presence of epicormic shoots in some lower stems reduced the volume of clear timber grades. The PLI scores for the 13 study trees were much lower than those for radiata pine, mainly because of a lack of strict control over the defect core (early pruning) and regular removal of epicormic shoots. Higher PLI values (and hence value recovery) can be expected from redwood stands grown under strict management practices (regular thinning, pruning and epicormic removal).

The amount of heartwood present in redwood logs is variable (Cown and McKiney 2009) and an important determinant of the financial value because it impacts on the value of timber grades. Future crops would benefit from careful site selection, genetic selection (to enhance growth and heartwood development) and targeted silviculture.

Authors' contributions

DC was involved in initial planning of the study and coordinated the final write-up. HM carried out the analyses and prepared some of the figures for the report. PS organized the tree measurements, was responsible for the sawmill study and assisted with the report writing. DM assisted with finalization of the manuscript. All authors read and approved the final manuscript.

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