DIVERSIFIED SPECIES TECHNICAL NOTE

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Heartwood of Coast Redwood in New Zealand and Prediction of its Durability using Near-infrared Spectroscopy

Summary

The heartwood of coast redwood is valued for its red colour and natural durability, but little is known about how these vary in the New Zealand resource, and how they can be managed. With this in mind, we evaluated the heartwood of plantation-grown coast redwood trees in three North Island forests, and assessed the use of near-infrared (NIR) spectroscopy as a method of predicting the natural durability of heartwood.

The coast redwood trees were of different age and seedlots in each of the forests, so the effects of site and genetics were confounded, but they did provide a wide range of heartwood properties. The butt log and breast height disc measurements showed the heartwood content was strongly influenced by the age and size of the trees, and the heartwood red colour, basic density, and natural durability appeared to be largely determined by the individual trees.

The near-infrared (NIR) spectra of the heartwood gave good predictions of weight loss with fungal decay testing, and could be used to screen the heartwood of coast redwood trees for natural durability. The methods that were assessed can be applied to increment cores, for the selection of clones, and to sawn boards to improve the utilisation of the current resource.

The evaluation of clonal trials, such as the Kuser clones, could be used in future research to determine the effect of site and genetics on heartwood durability, but the trees will need to be 20 years of age for sufficient heartwood development to occur. The application of the NIR models for the prediction of natural durability will require further development and testing to ensure they are accurate when applied to coast redwood trees from different sources.

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Introduction

The heartwood of coast redwood (*Sequoia sempervirens*) is a naturally durable alternative to preservative treated pine at H1.1, H1.2, and H3.1 treatment levels [1]. The heartwood of mature trees is moderately durable in ground contact [2,3], and durable in above-ground situations, but shows considerable variation in natural durability [4].

Current methods of decay testing with in-ground grave-yard tests of stakes [5] and *in vitro* tests with fungal cultures [6, 7] are time consuming and require a large number of samples. Faster methods that can estimate the natural durability of heartwood and be applied to tree breeding programmes and to grade the heartwood of the current resource are needed.

Near-infrared (NIR) spectroscopy is a potential method for rapidly assessing the natural durability of heartwood, and has shown encouraging results for larch species [8, 9], Scots pine [10, 11], Norway spruce and European beech [12]. The method relates the NIR spectra of the heartwood to the weight loss associated with fungal decay, using calibration models based on partial least squares (PLS) regression.

In this study, the natural durability of coast redwood heartwood from three North Island forests, and its prediction using NIR spectroscopy, was evaluated using *in vitro* decay testing of heartwood blocks with fungal cultures.

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Methods

The coast redwood trees were sampled from stands at Kinleith Forest in the Waikato, Mangatu Forest in Gisborne, and Rotoehu Forest in the Bay of Plenty (Table 1). The trees in each forest stand were of different ages and seedlots, so the effects of site and genetics are confounded, but the stands did provide a wide range of tree age and New Zealand and Californian seedlots. The stand inventories showed the Kinleith Forest stand had a stocking of 550 s/ha, basal area of 150.9 m^2/ha, mean DBH of 59.1 cm, and mean top height of 44.9 m, while the Mangatu Forest stand had a stocking of 398 s/ha, basal area of 107.6 m^2/ha, mean DBH of 58.5 cm, and mean height of 32.8 m.

Wood discs were cut from the ends of the 6 m butt log for six trees at Kinleith Forest and thirteen trees at Mangatu Forest, and at breast height for 32 trees at Rotoehu Forest. The wood basic density and heartwood content were measured, and heartwood blocks of dimensions 25 × 15 × 50 mm (tangential, radial, longitudinal directions) were cut in series from the inner to outer heartwood of radial strips from each disc.

The heartwood blocks were measured on the radial longitudinal surfaces for colour using a Minolta CR-400 Chroma meter, and for near-infrared (NIR) spectra using a Bruker MPA spectrometer connected to fibre-optic probe with a 4 mm diameter spot (Fig. 1), and an NIR line camera [13] (Fig. 2). The NIR spectral data of the camera were limited in resolution and range compared to the Bruker spectrometer.

Table 1: Description of coast redwood stands.

Descriptor	Kinleith	Mangatu	Rotoehu
Planted	1932	1970	1981
Tree age (years)	71	38	22
Latitude	38° 04’	38° 16’	37° 54’
Longitude	175° 54’	177° 51’	176° 32’
Altitude (m)	240	200	120
Average annual temperature (°C)	12.7	13.2	13.4
Average annual rainfall (mm)	1740	1368	1764

Figure 1: Fibre-optic probe used with the Bruker spectrometer, showing a close-up of the optical fibres on the probe tip (inset).

Figure 2 : NIR line camera used to acquire hyperspectral images of the heartwood blocks.

The fungal decay resistance of the coast redwood heartwood blocks, and radiata pine sapwood blocks, was evaluated using pure fungal culture decay testing (Fig. 3) with the European Standards EN 113 [6] and EN 350-1 [7]. The heartwood blocks of each radial strip were allocated to the fungal cultures, from inner to outer heartwood, in the repeating sequence:

brown-rot *Coniophora puteana,* brown-rot *Gloeophyllum trabeum*, white-rot *Trametes versicolor*. The radiata pine sapwood blocks ~~were used as a control, and~~ were randomly allocated to each of the three fungal cultures.

The heartwood blocks were assigned to natural durability classes on the basis of their x value, calculated using the equation:

$$x\ value = \frac{average\ mass\ loss\ of\ the\ test\ specimens}{average\ mass\ loss\ of\ the\ reference\ specimens}$$

Where: the test specimens were the coast redwood heartwood blocks, and the reference specimens were the radiata pine sapwood blocks.

Figure 3: Decay testing of the coast redwood heartwood, and radiata pine sapwood, blocks with fungal cultures.

The stand level data were compared using one-way analysis of variance (ANOVA), and the sources of variation were calculated using SAS procedures. The NIR spectra were processed, and the partial least squares (PLS) regressions calculated for the prediction of heartwood weight loss for coast redwood with decay testing, using The Unscrambler software.

Results

Diameter at Breast Height

The diameter at breast height (DBH) of the selected coast redwood trees increased with stand age (Fig. 4). The average DBH of the Mangatu Forest trees was similar to the stand average (58.5 cm), but the selected? Kinleith Forest trees were all larger than the stand average (59.1 cm). The forest stands were the largest source of variation in DBH (Table 2), reflecting the large differences in the tree age of the forest stands and the selection of larger trees in the Kinleith Forest stand.

Heartwood Content

The heartwood content increased with stand age, and tree size (Fig. 4 and 5). The average heartwood content of the 38 year-old Mangatu Forest trees was similar to that of 45-year-old coast redwood trees from Tauranga [14], but the heartwood content of the 71-year-old Kinleith Forest trees was higher. The trees selected from the Kinleith Forest stand were larger than the stand average, so the heartwood content would be higher than expected for this stand, since the heartwood content increases with the size of the trees (Fig. 5). The forest stands were the largest source of variation in heartwood content (Table 2), due to the large differences in tree age and size of the forest stands.

Table 2: Sources of variation in diameter and wood properties for the coast redwood trees at Kinleith, Mangatu, and Rotoehu Forests.

Property	Variance components (%)		
	Forest	Tree	Within Tree
DBH	83	17	
Heartwood content[1]	67	33	
Heartwood a* colour[2]	0	36	64
Basic density[3]	0	64	36

[1] Heartwood content at 6 m height for Kinleith, Mangatu Forest.
[2] Heartwood a* colour at 0 m height for Kinleith, Mangatu Forest.
[3] Basic density (rings 21-30) at 0 m and 6 m height for Kinleith, Mangatu Forest.

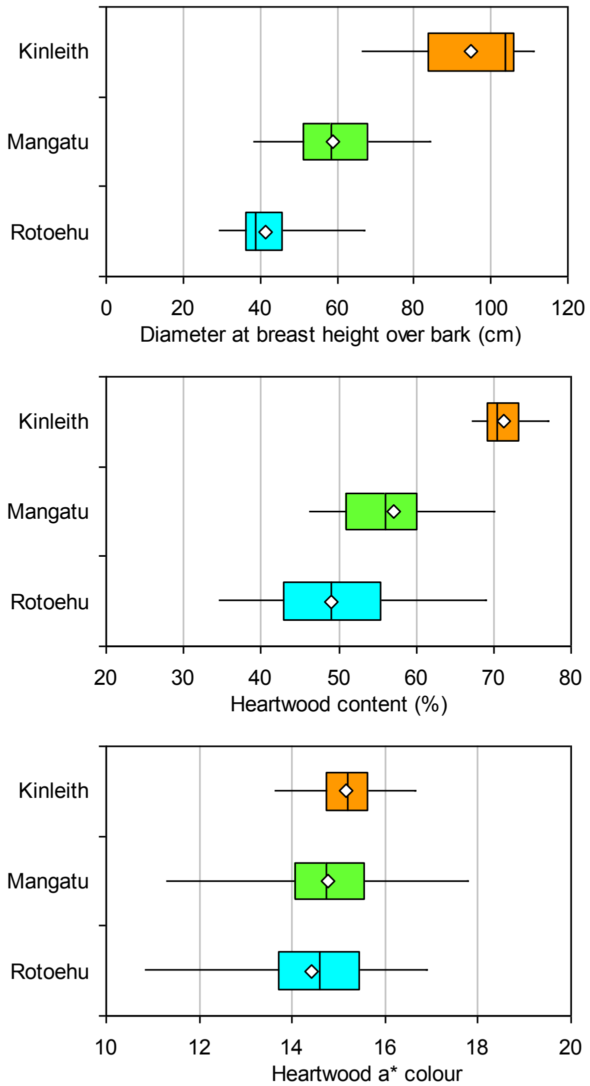

Figure 4: ***Box-and-whisker plots of the diameter at breast height, and heartwood content at 6 m height, heartwood a* (red) colour at 0 m and 6 m height for Kinleith and Mangatu Forests, and breast height for Rotoehu Forest. Diamond symbols show the average, horizontal boxes the median, 25th and 75th percentiles, and the horizontal lines extend to the minimum and maximum values.***

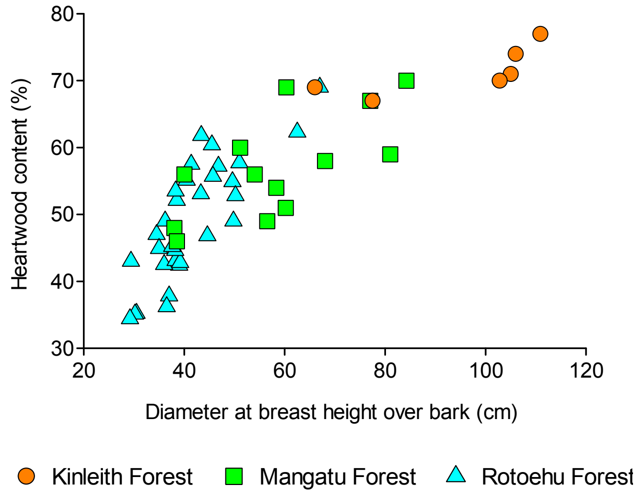

Figure 5: ***Heartwood content at 6 m height for Kinleith and Mangatu Forest, and breast height for Rotoehu Forest, as a function of diameter at breast height (DBH) for the coast redwood trees.***

Heartwood Colour

The heartwood a* (red) colour showed only small differences between the forest stands (Fig. 4). Most of the variation in heartwood a* colour occurred among the trees and from inner to outer heartwood (Table 2). The radial trends of heartwood a* colour, from inner to outer heartwood, were not consistent for the trees of each forest stand.

Wood Density

The basic density of the wood at the Kinleith and Mangatu Forest stands was similar for growth rings 21-30 at 0 m and 6 m height, but higher than for growth rings 1-22 at breast height in the Rotoehu Forest trees (Fig. 6). Most of the variation in basic density occurred among the trees at the Kinleith and Mangatu Forest stands, with some variation within the butt log due to the small decline in basic density from 0 m and 6 m height (Table 2). The basic density at Kinleith and Mangatu Forests was similar to that of 45-year-old coast redwood trees from Tauranga [14], and second-growth coast redwood trees in California [15, 16].

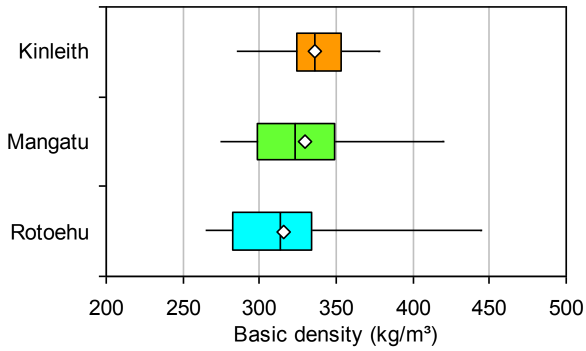

Figure 6: Box-and-whisker plots of the basic density at 6 m height for Kinleith and Mangatu Forests, and breast height for Rotoehu Forest.

Decay Resistance

The heartwood of coast redwood was resistant to decay by the brown-rot (*G. trabeum*) and white-rot (*T. versicolor*) fungal cultures, but was less resistant to decay by the brown-rot (*C. puteana*) fungal culture (Table 3, Fig. 7). The heartwood of the Kinleith and Mangatu Forest stands had greater resistance to fungal decay, as measured by the weight loss, which could be attributed to the older trees in these stands. Most of the weight loss variation with the fungal cultures occurred within the trees, from the inner to outer heartwood (Table 4, Fig. 8).

The heartwood weight loss was high for the first ten growth rings from the pith (Fig. 8), but showed a large decrease over these growth rings, and was much lower for rings 11 to 40, with the brown-rot (*C. puteana*) fungal culture.

Table 3: Comparison of weight loss with the fungal cultures for the coast redwood heartwood and radiata pine sapwood blocks.

Source	Weight loss of blocks (%)		
	Brown-rot *C. puteana*	Brown-rot *G. trabeum*	White-rot *T. versicolor*
Coast redwood			
Kinleith - 0 m	9.0 b	1.2 b	0.8 b
Kinleith - 6 m	12.6 b	1.5 b	0.6 b
Mangatu - 0 m	12.0 b	2.4 b	1.8 a
Rotoehu - BH	21.5 a	4.9 a	2.2 a
Radiata pine	35.5	38.5	11.3

Average values followed by the same letter do not differ significantly between the forests for each fungal culture ($p > 0.05$).

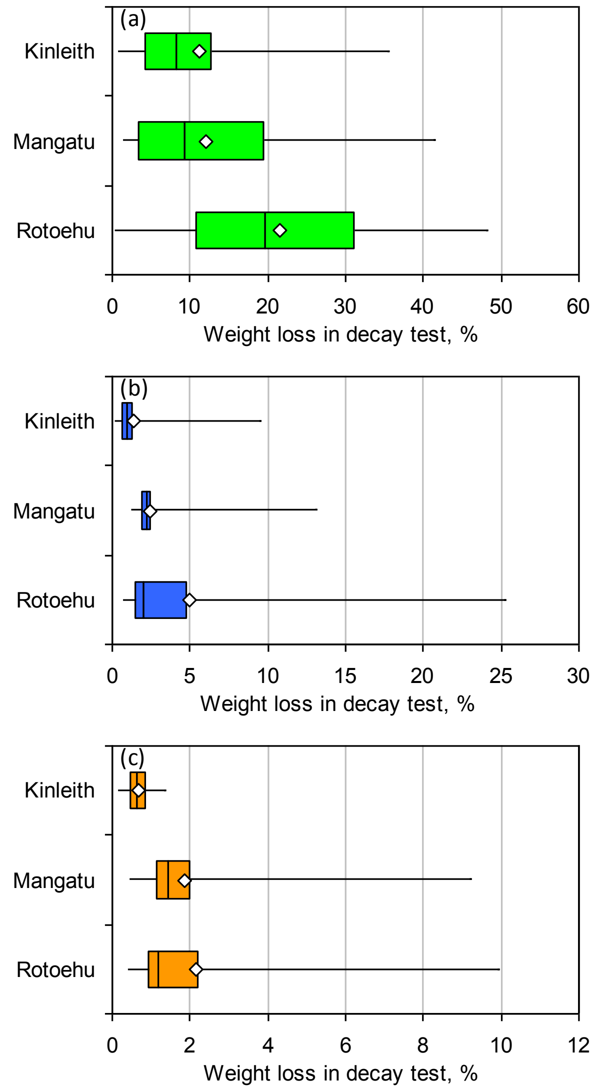

Figure 7: Box-and-whisker plots of the heartwood weight loss for the coast redwood from Kinleith, Mangatu, and Rotoehu Forests with (a) brown-rot C. puteana, (b) brown-rot G. trabeum, (c) white-rot T. versicolor.

The radial trends of weight loss were similar to old- and young-growth coast redwood trees in California [17]. The individual trees from Rotoehu Forest showed large differences in heartwood weight loss for the first ten growth rings (Fig. 9), with some trees showing lower heartwood weight loss from an early age. This suggests there may be potential for genetic improvement in the fungal decay resistance of heartwood in this species.

Table 4: ***Sources of variation in heartwood weight loss with the fungal cultures, at 0 m height for the coast redwood trees at Kinleith and Mangatu Forests.***

Fungal culture	Variance components (%)		
	Forest	Tree	Within Tree
C. puteana	0	2	98
G. trabeum	21	3	76
T. versicolour	24	5	71

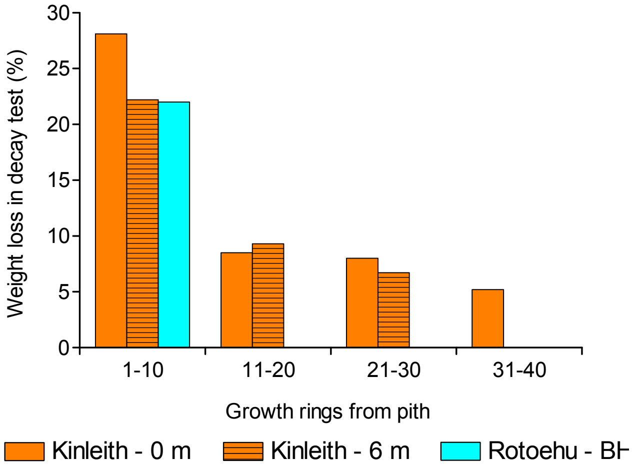

Figure 8: ***Weight loss for growth ring number from the pith, with the brown-rot (C. puteana) fungal culture, for the coast redwood trees from Kinleith and Rotoehu Forests.***

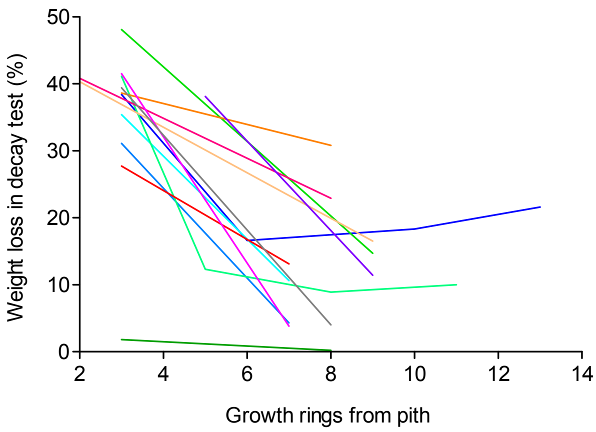

Figure 9: ***Weight loss for growth ring number from the pith, with the brown-rot (C. puteana) fungal culture, for the individual coast redwood trees from Rotoehu Forest.***

The natural durability of the coast redwood heartwood blocks ranged from very durable (class 1) to not durable (class 5). The heartwood of the Kinleith Forest trees was classified on average at 0 m height as durable (class 2), and at 6 m height as moderately durable (class 3). The heartwood of the Mangatu Forest trees at 0 m height was moderately durable (class 3), and the heartwood of the Rotoehu Forest trees at breast height was slightly durable (class 4).

The frequency of the heartwood blocks in each natural durability class differed between the coast redwood stands (Table 5). The very durable and durable (class 1 & 2) heartwood comprised 72% and 56% of the heartwood blocks at 0 m height in Kinleith and Mangatu Forest, respectively, and 26% of the heartwood blocks at breast height in Rotoehu Forest. The forest stands all contained heartwood that was slightly durable (class 4) and not durable (class 5), which indicates there is a clear need to classify the heartwood based on natural durability.

Table 5: ***Frequency of the heartwood blocks in durability classes, for heights in the Kinleith, Mangatu, and Rotoehu Forests trees, with the brown-rot (C. puteana) fungal culture.***

Durability class	Frequency of heartwood blocks (%)			
	Kinleith 0 m	Kinleith 6 m	Mangatu 0 m	Rotoehu BH
1	29	41	38	12
2	43	18	18	14
3	21	18	22	26
4	7	9	16	24
5	0	14	6	24

Durability class: 1 - very durable, 2 - durable, 3 - moderately durable, 4 - slightly durable, 5 - not durable.

Near-infrared Spectroscopy

The near-infrared (NIR) spectra of the coast redwood heartwood blocks was useful in predicting the weight loss with the brown-rot (*C. puteana*) fungal culture (Table 6, Fig. 10). The partial least squares (PLS) regression model with the Bruker spectrometer gave good predictions of weight loss, with some separation of the natural durability classes.

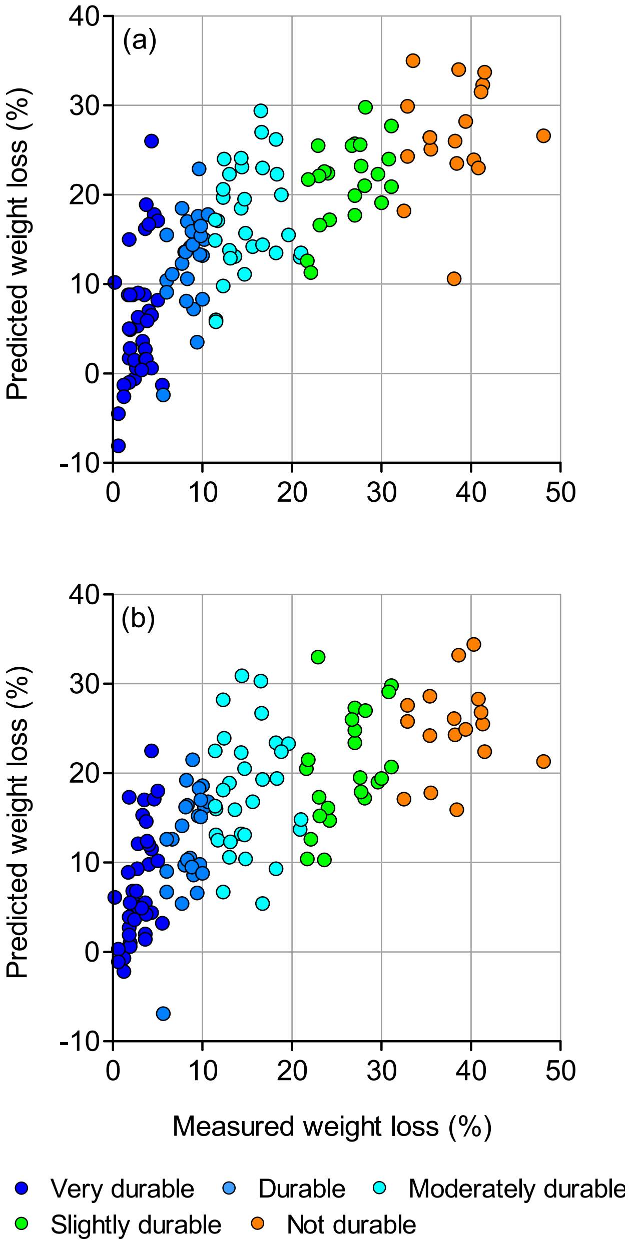

***Figure 10:* The relationship between the measured and predicted weight loss, with the brown-rot (C. puteana) fungal culture, for PLS regression models with (a) Bruker spectrometer, (b) NIR line camera.**

The PLS regression model could be used to screen coast redwood trees for natural durability, using increment cores or radial strips and the Bruker spectrometer's custom-built linear transport system and fibre-optic probe [18]. This would provide radial measurements of natural durability from inner to outer heartwood, and comparison of coast redwood trees on the basis of the radial trends of natural durability.

The NIR line camera was less effective in predicting the weight loss with the brown-rot (*C. puteana*) fungal culture (Table 6, Fig. 10). The standard deviation of the predicted weight loss (RMSEP) was larger than for the Bruker spectrometer, which means the estimates of weight loss were less precise. The NIR line camera produces spectra of a much lower resolution, and narrower wavelength range, compared to the Bruker spectrometer, so it contains less information about the chemistry of the heartwood. There is some potential in this method, but improvements in the resolution of the NIR spectra would be needed for effective prediction of the natural durability of the heartwood.

***Table 6:* PLS regression models for weight loss prediction of the coast redwood heartwood blocks with the brown-rot (C. puteana) fungal culture.**

Descriptor	Bruker spectrometer	NIR line camera
R^2 (CAL)	0.58	0.50
R^2 (CV)	0.52	0.42
RMSEC	7.9	8.5
RMSEP	8.4	9.2
No. of PCs	6	7

CAL, calibration; CV, cross-validation; RMSEC, root mean square error of calibration; RMSEP, root mean square error of prediction; PC, principal components.

Conclusions

Coast redwood trees from North Island forest stands, with a wide range of tree age and seedlots, showed the heartwood content was strongly influenced by tree age and size, and the heartwood durability, a* (red) colour, and basic density were largely determined by the individual trees.

The near-infrared (NIR) spectra of the heartwood could be used to screen coast redwood trees for natural durability. The Bruker

spectrometer at CSIRO gave the best predictions of weight loss with fungal decay testing.

The natural durability improved from inner to outer heartwood, so it is recommended that increment cores or radial strips are used with the Bruker spectrometer so that coast redwood trees are compared on the basis of the radial trends of natural durability.

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