Prediction of the Decay and Termite Resistance of Western Red Cedar Heartwood

Rod Stirling
Paul I. Morris
J. Kenneth Grace

Abstract

Western red cedar (WRC; *Thuja plicata*) is highly valued for its natural durability. Rapid methods to assess heartwood durability are needed to identify breeding stock that will ultimately yield trees with durable wood when harvested. Chromatographic methods to detect heartwood extractives have been developed, but these still require significant time and laboratory resources and rely upon an understanding of the relationship between extractives and durability that is still incomplete. Visible/near-infrared (VIS/NIR) spectroscopy combined with multivariate statistical analysis has been used to rapidly predict a wide range of wood properties, including extractive content and decay resistance. The present work investigates the ability of VIS/NIR spectroscopy to predict extractive content, decay resistance, and termite resistance of WRC heartwood and explores the association between extractive content and durability. Partial least squares (PLS) models based on VIS/NIR spectra had moderate predictive ability for lignans, plicatic acid, beta-thujaplicinol, and total extractives. Other extractives were poorly predicted. Developed PLS models were not predictive for decay resistance but were moderately predictive of termite resistance. Decay and termite resistance were not strongly associated with any measured extractive. A moderately strong correlation was observed between termite resistance and red coloration (a*). Some of the models developed may be suitable for screening, but none are accurate enough for phenotyping.

Western red cedar (WRC; *Thuja plicata*) is highly valued for its decay resistance and, to a lesser degree, for its termite resistance. Decay resistance varies both between and within trees (Cartwright 1941, Englerth and Scheffer 1955, Scheffer 1957, DeBell et al. 1999, Freitag and Morrell 2001). Decay resistance tends to increase radially from pith to the heart–sap boundary and longitudinally from crown to base. Building products cut from different trees and different parts of the tree thus have differing decay resistance. In field decay tests WRC wood product performance is variable but considerably better than that of nondurable species (Flæte et al. 2011, Morris et al. 2011). The European standard EN 350-2 (European Committee for Standardization [CEN] 1994) lists North American–grown WRC as Class 2 (durable), while UK-grown WRC is listed as Class 3 (moderately durable). Similarly, the Australian standard, AS5604 (Standards Australia 2005), lists WRC as Class 2 for above-ground use and Class 3 for in-ground use, where Class 1 is most resistant and Class 4 is least resistant.

The termite resistance of WRC is also highly variable. In laboratory tests with *Coptotermes formosanus* (Formosan subterranean termite) there are reports of relatively low resistance (Mannesmann 1973, Morales-Ramos and Rojas 2001) and relatively high resistance (Su and Tamashiro 1986, Taylor et al. 2006, Ohmura et al. 2011). Similarly, against *Incisitermes minor,* performance has been variable (Rust and Reierson 1977, Indrayami et al. 2007). Laboratory and field tests against *Reticulitermes speratus* have shown moderately good, but variable, performance (Ohmura et al. 2011). Laboratory and field tests against *Reticulitermes flavipes* have shown highly variable resistance (Carter and Smythe 1974, Morris et al. 2009, Kirker et al. 2013). The European standard EN 350-2 (CEN 1994) lists WRC as susceptible to termites, while the Australian standard AS5604 (Standards Australia 2005) lists WRC as resistant

The authors are, respectively, Senior Scientist, Wood Protection, and Research Leader—Wood Protection, FPInnovations,Vancouver, British, Columbia, Canada (rod.stirling@fpinnovations.ca [corresponding author], paul.morris@fpinnovations.ca); and Associate Dean for Research College of Tropical Agric. and Human Resources, Univ. of Hawaii at Manoa (kennethg@hawaii.edu). This paper was received for publication in June 2014. Article no. 14-00056.
©Forest Products Society 2015.
Forest Prod. J. 65(3/4):84–92.
doi:10.13073/FPJ-D-14-00056

to termites under protected above-ground conditions. Variations among test materials, termite populations, and test methods would have contributed to these differences in performance and standardization.

It is important that natural durability be maintained in future forests to resist root- and trunk-rot fungi and in future harvests to yield durable lumber (Daniels and Russell 2007, Russell and Daniels 2010). Identifying breeding stock that produces highly durable heartwood is a time-consuming task, as the trees must be sampled and the wood tested for durability against degrading organisms. Rapid methods to assess heartwood durability are therefore needed.

Heartwood color can provide some indication of decay resistance, though the relationship is the opposite in WRC of that in many other species. Lighter, straw-colored heartwood often contains more extractives and is more resistant to decay than brown heartwood (MacLean and Gardner 1956). However, there are exceptions, and wood color alone is not considered to be a sufficiently accurate indicator of decay resistance.

The decay and termite resistance of WRC heartwood is well known to be associated with the presence of extractives, and extractive production has been found to be a heritable trait (Russell and Daniels 2010). Methods have been developed to measure extractives for use as a proxy for durability (Daniels and Russell 2007). Chromatographic analysis of extractives still requires significant time and laboratory resources. Moreover, such data are difficult to use without a fuller understanding of the relationship between individual extractives and durability.

The thujaplicins are highly toxic to decay fungi in vitro (Rennerfelt 1948) but deplete rapidly in field tests (Johnson and Cserjesi 1980) and have not been strongly associated with decay resistance in laboratory tests (DeBell et al. 1997) or field tests (Morris and Stirling 2012). The lignans, including plicatic acid, are reported to have mild fungal toxicity (Roff and Atkinson 1954), but they are present after long-term field exposure (Stirling 2010) and had the greatest association with decay resistance in field tests (Morris and Stirling 2012). The compounds contributing to termite resistance have received less attention and may be different from those contributing to fungal resistance (Barton et al. 1972). Taylor et al. (2006) found only weak correlations between weight loss from *Postia placenta* and weight loss from *C. formosanus*. Mechanisms other than direct fungal toxicity, such as reduced equilibrium moisture content (Stirling and Morris 2006) or radical scavenging properties (Stirling et al. 2007) may account for much of WRC's durability.

Given the lack of certainty in the relationship between specific extractives and decay or termite resistance, an alternative approach was considered. Visible/near-infrared (VIS/NIR) spectroscopy, when combined with multivariate statistical modeling, can be used to predict a wide range of chemical and physical wood properties. Extractive content has been predicted from NIR spectra of eucalyptus (Baillères et al. 2002, Poke and Raymond 2006), *Goncalo alves* (Taylor et al. 2008), and teak (*Tectona grandis*; Niamké et al. 2014). Baillères et al. (2002) went on to suggest that NIR would be a useful tool for rapidly identifying trees with desirable traits for breeding. Decay resistance has been predicted from NIR spectra in larch heartwood (Gierlinger et al. 2003, Sykacek et al. 2006) and in Scots pine heartwood (Flæte and Haartveit 2004). No reports of using NIR to predict termite resistance were found, although this approach has been suggested by Kijidani et al. (2012).

The present work investigates the ability of VIS/NIR spectroscopy to predict extractive content, decay resistance, and termite resistance of WRC heartwood and explores the association between extractive content and durability.

Experimental Methods

Modeling extractive concentrations

Twenty-five frozen WRC disks from a previous study (Daniels and Russell 2007) were selected. These disks had been frozen to protect the extractives from biodegradation. Based on previous experiments, the freezing process was not anticipated to have significant effects on extractives chemistry. Fourteen of the samples came from sites in coastal British Columbia; 11 came from sites in British Columbia's interior wet belt. Two samples were old growth; the remainder were second growth. Disks came from various heights on the trees. Strips (12 by 12 mm) were cut from pith to bark, or bark to bark through the pith, from each disk. All strips were air-dried, measured into 12-mm segments, and labeled on the cross-sectional faces. Visual observations of decay, staining, pith, knots, and sapwood/heartwood were made for each section. One of the radial faces of each strip was sanded with 280-grit sandpaper.

A sample holder was fabricated that allowed the sample to slide beneath the VIS/NIR light source. A 12-mm opening allowed illumination and data collection from a known area while blocking stray light. VIS/NIR spectra were collected from the sanded radial face of each 12-mm section of each strip. A reflectance reference was scanned once per hour with a Spectralon reference block to account for variations in light intensity and environmental conditions. Reflectance spectra were obtained from 350 to 2500 nm using an ASD Labspec 5000 VIS/NIR spectrometer (Boulder, Colorado) with 1-nm resolution.

After scanning, each segment was chopped into 12-mm sections that corresponded to where the spectra had been collected. These 12-mm cubes were chopped into splinters and extracted and analyzed for extractive content by the high-performance liquid chromatography method of Daniels and Russell (2007). Plicatic acid, thujaplicatin methyl ether, alpha-, beta-, and gamma-thujaplicin, beta-thujaplicinol, thujic acid, and methyl thujate were quantified. In addition, the peak area ratio for plicatin was determined, since no pure standard was available to quantify this compound.

Samples from five preselected disks (three coastal, two interior) were excluded from model development to serve as an external validation data set ($n = 121$). In addition, 26 samples with noted deformities (e.g., knots, pith, or insect damage) were also excluded. The remaining samples ($n = 293$) were used to develop partial least squares (PLS) models to predict extractive concentrations using Grams AI 8.0 with PLSplus/IQ (Thermo Electron Corp.). The PLS technique is a form of regression analysis that is useful for parameter selection in the regression analysis and the building of the model. PLS works by identifying orthogonal principal components from spectral data and concentration data matrices that maximize covariance between the data sets. The PLS-1 algorithm with full cross validation was used for all models. Extractives were modeled individually, and collectively, as identifiable lignans (plicatic acid and

thujaplicatin methyl ether), thujaplicins (alpha, beta, and gamma-thujaplicin and beta-thujaplicinol), other terpenes (thujic acid and methyl thujate), and total identifiable extractives (sum of quantified extractives). These models were then used to predict the concentration of extractives in external validation data sets. Root mean standard error of cross validation (RMSECV) was calculated to provide an indication of model accuracy based on the sequential exclusion and prediction of samples from the calibration data set. Root mean standard error of prediction (RMSEP) provided an indication of model accuracy using an external validation data set and is therefore a better estimate of future performance of the model. Low RMSECV and RMSEP values indicate better model performance. Relative prediction error (RPE) was calculated to enable comparison of model accuracy between extractives data sets. An RPE close to 1 indicates very accurate prediction, while zero or negative values indicate poor prediction (Meder et al. 2002). Optimized extractives models used spectra that were mean centered, variance scaled, and adjusted with the multiplicative scattering correction (MSC). Other preprocessing techniques were investigated, including taking the first and second derivatives of the spectra, modeling selected regions, and excluding sapwood samples. Models to predict extractives concentrations based on these data were not fully developed, as they did not improve performance.

Modeling decay and termite resistance

Experimental design was based in part on that of Flæte and Haartveit (2004). From each of the WRC disks described above, samples were cut from the inner heartwood and the outer heartwood (Fig. 1). Inner heartwood samples were taken at a location centered on 1/3 the distance from the pith to the heart–sap boundary. Outer heartwood samples were taken as close to the heart–sap boundary as possible without including any sapwood. End grain previously exposed on the disk was not included in any of the samples. From each sampling location a 14-mm (radial) by 70-mm (tangential) piece was cut. Each piece was then cut into three 14-mm rows surrounded by 1-mm strips. Four cubes were cut from each 14-mm piece. The 1-mm strips were ground to pass through a 20 mesh screen and analyzed for extractives as described above. Averaged extractive data from strips cut above and below the test blocks were associated with these blocks. Two cubes from each row were allocated to decay testing and two to termite testing.

The 14-mm cubes were conditioned to constant weight at 40°C. VIS/NIR spectra were obtained from each radial surface as described above. Block surfaces were not sanded, as earlier work demonstrated that this was not necessary to collect high-quality spectra from the relatively smooth sawn faces of the blocks. The two spectra obtained from each block were averaged and used to model decay and termite resistance.

Leaching and accelerated aging to promote biodegradation of extractives were used to simulate long-term performance in service before initiating decay and termite tests. Blocks were leached based on the methods outlined in AWPA E10 (American Wood Protection Association 2009). Water was changed after 1, 2, 5, 7, 9, and 12 days. Blocks were removed on day 14 and allowed to air-dry. The blocks were then exposed to conditions conducive to the growth of detoxifying organisms in an uninoculated mold box at 25°C and close to 100 percent relative humidity for 6 weeks

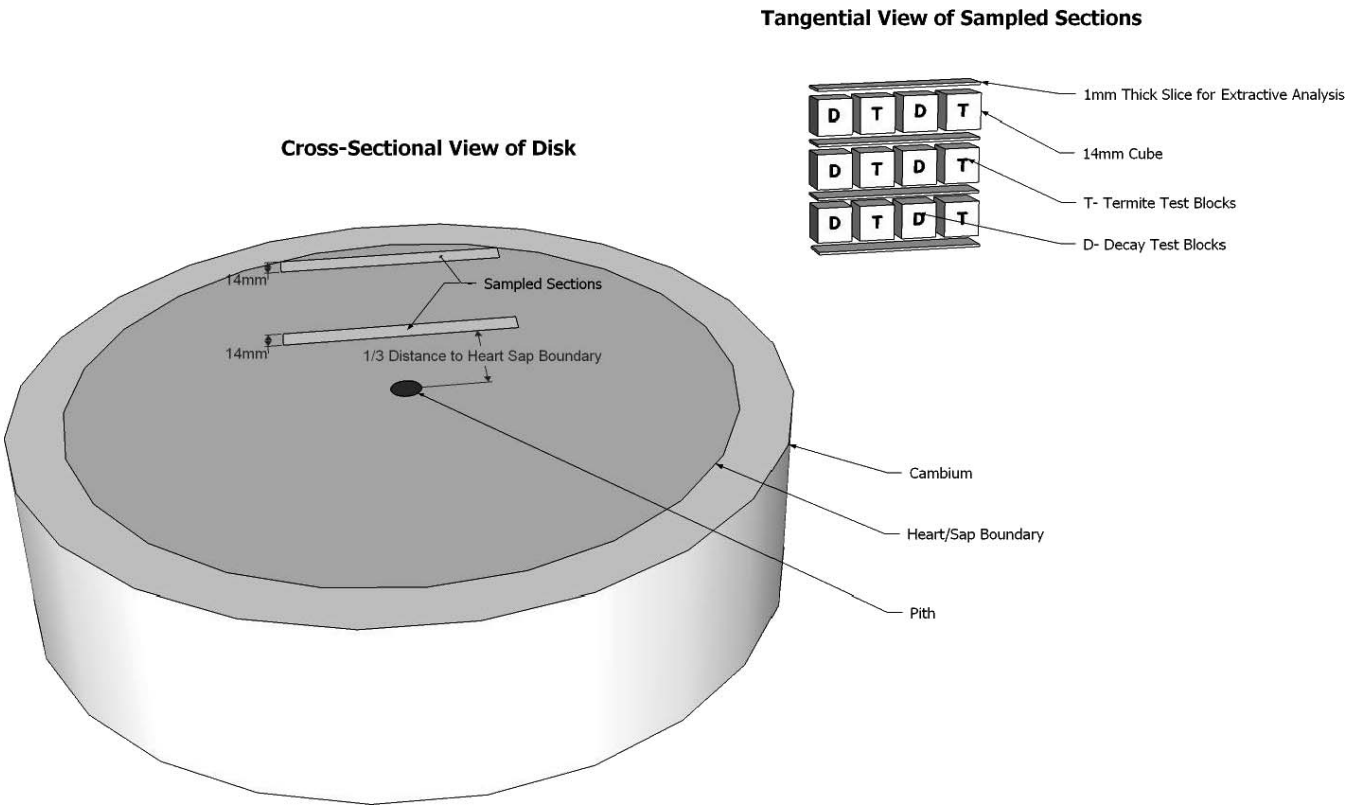

Figure 1.—Diagram showing sampling locations from each disk.

according to the methods of Stirling and Morris (2011). Blocks were removed from these chambers and stored outside for approximately 1 hour at weeks 0, 2, and 4 to provide an opportunity for inoculum to reach the samples. The blocks were then reconditioned at 40°C and weighed.

Blocks for decay testing were weighed, vacuum sealed in polyethylene, and sterilized by 25 kGrays of ionizing radiation. Cylindrical glass jars (500 mL) were half-filled with soil (horticultural loam) that was adjusted to approximately 50 percent moisture content. The soil was topped with two 3 by 29 by 35-mm southern pine sapwood feeder strips, and the assembly sterilized by autoclaving at 103.4 kPa and 121°C for 1 hour with 5 minutes of drying. After cooling on a clean air bench, each jar was inoculated with *Coniophora puteana* (Schum. ex Fr.) Karst., Ftk 9G from the edge of colonies on plates containing 1 percent malt extract agar (Oxoid). *C. puteana* was chosen because it is moderately resistant to WRC extractives and produces high weight losses in WRC in laboratory decay tests (Chedgy et al. 2009, Stirling and Morris 2010) and had been noted by the authors fruiting on WRC trees. Following inoculation, jars were closed with a vented sterile lid. The jars were incubated at 25°C and 80 percent relative humidity for 6 weeks before the test blocks were added. Two blocks from different groups were placed in each jar. The jars were incubated following ASTM D2017 methods (ASTM International 2005). Pine sapwood control blocks were removed after 7, 8, 9, and 10 weeks of incubation. At 10 weeks, weight loss in the pine sapwood controls that were removed reached 50 percent, and the remaining blocks were removed from the test, conditioned, and weighed.

Blocks for termite testing were challenged with *C. formosanus* Shiraki (Formosan subterranean termites) in a modified no-choice AWPA E1 test (AWPA 2012). Owing to limited testing capacity, samples were evaluated in different batches. One replicate from each sampling location was included in each batch to prevent bias caused by interbatch variability. Batches 1 and 2 were conducted using 200 Formosan subterranean termites, with 180 workers and 20 soldiers (10%) in each test jar to reflect normal caste proportions in a termite colony. Owing to collection difficulties, the number of termite soldiers in each test jar had to be reduced slightly for batches 3, 4, and 5. For these batches 180 workers and 10 soldiers were used. Although the effect of minor differences in soldier numbers was not quantified, the test period was extended by 1 day for batches 3 to 5 under the assumption that the reduction in termite numbers would logically slightly reduce feeding rate (although soldiers do not feed directly, they must be fed by the workers). Thus, batches 1 and 2 ran for 14 days, while batches 3, 4, and 5 ran for 15 days. Each test jar contained 75 g of silica sand, and 15 mL of distilled water (half the quantities used in the usual AWPA E1 test, with wafers weighing twice as much as the samples in this test). Each sample was placed on the surface of the damp sand, and then freshly collected and counted termites (collected in wooden traps from a colony on the campus of the University of Hawaii at Manoa) were added to the sand surface. Jars were kept in an unlighted incubator at 28°C. After 14 and 15 days, the wood samples were removed carefully, brushed free of sand, oven-dried at 40°C for 48 hours, placed in a desiccator for 60 minutes at laboratory conditions, and weighed to determine mass loss. Live termites in each jar were counted to determine mortality.

Observations from the initial two batches of termite testing suggested that measurement in the visible region of the spectrum might be predictive of termite resistance. To test this hypothesis, colorimetric data (L*a*b*) were collected from the radial faces of each remaining block using a Konica Minolta CM-700d spectrophotometer and correlated with termite resistance in WRC. L* measures lightness on a scale from 0 to 100, a* indicates green (negative) and red (positive) coloration, and b* indicates blue (negative) and yellow (positive) coloration.

Correlations between decay and termite resistance, extractive concentrations, and colorimetric data were determined using SPSS. The optimized PLS model to predict decay resistance from VIS/NIR spectra used first-derivative spectra (240 calibration samples, 60 validation samples). The optimized PLS model developed to predict termite resistance from VIS/NIR spectra used first-derivative spectra from 425 to 1800 nm (209 calibration samples, 41 validation samples).

Results and Discussion

Extractives prediction

Extractive concentrations ranged widely in the test data set (Table 1) and were similar to literature values (Daniels and Russell 2007). Because the present data set included sapwood, the minimum values were almost all zero. PLS models were developed for each extractive and class of extractives. None of the developed models had a high degree of accuracy, but several performed moderately well (Figs. 2 through 6). Note that the lines in these figures show where predicted data equal measured data; they are not indicative of linear regression. Models for lignans, plicatic acid, beta-thujaplicinol, and total extractives all had RPE $>$ 0.6 and r^2 (validation) $>$ 0.70. The lignans model largely reflected the correlation with plicatic acid, because plicatic acid was the major constituent of the measured lignans, and thujaplicatin methyl ether was poorly predicted. PLS models were somewhat predictive of total thujaplicin concentration but less able to predict the concentrations of individual thujaplicins (with the exception of beta-thujaplicinol). Inasmuch as fungal toxicities of the thujaplicins are comparable (Rennerfelt 1948, Roff and Whittaker 1959, Stirling et al. 2007), it is the total amount of thujaplicins that is of interest. Prediction of the abundance of plicatin was also fair. The developed models could potentially be used as screening tools to select wood high (or low) in these extractives. The nonthujaplicin terpenes were poorly modeled (RPE $<$ 0). There was a tendency to overestimate the concentration in samples with low levels of terpenes and to underestimate the concentration in samples with high levels of terpenes (Fig. 4). Similar, or worse, predictive abilities were found for thujic acid and methyl thujate individually. The lack of sensitivity to the terpenes may be beneficial, because these compounds are not known to be associated with durability (Russell and Daniels 2010).

Decay

A wide range of weight losses was observed in the WRC blocks exposed to *C. puteana,* making the data set suitable for developing predictive models (Table 2). Weight loss classifications ranged from nonresistant to highly resistant (ASTM D2017). PLS models developed to predict decay resistance were poor (Fig. 7). Based on the present data set,

Table 1.—Summary of extractives concentrations and partial least squares model statistics using visible/near-infrared data.[a]

				Calibration			Validation		
Extractive	Min.	Max.	Mean (SD)	PC	RMSECV	R^2	RMSEP	R^2	RPE
Plicatic acid	0	19,091	2,221 (3,426)	6	2,191	0.68	1,536	0.71	0.66
Thujaplicatin methyl ether	0	4,289	650 (786)	6	433	0.69	625	0.46	−0.20
Lignans	0	22,254	2,871 (4,076)	7	2,491	0.70	1,871	0.70	0.64
Alpha-thujaplicin	0	2,530	431 (450)	9	351	0.49	325	0.34	0.06
Beta-thujaplicin	0	1,773	360 (347)	9	256	0.48	362	0.19	−0.49
Beta-thujaplicinol	0	1,797	259 (324)	9	173	0.76	149	0.74	0.66
Gamma-thujaplicin	0	2,371	695 (615)	4	370	0.62	535	0.46	−0.46
Thujaplicins	0	5,752	1,744 (1,313)	6	827	0.62	809	0.60	0.48
Thujic acid	0	9,741	2,638 (2,115)	9	1,414	0.44	1,940	0.53	−1.37
Methyl thujate	0	520	69 (78)	6	61	0.47	64	0.16	−0.12
Terpenes	0	9,882	2,707 (2,125)	9	1,417	0.44	1,917	0.55	−1.16
Total	4.3	30,546	7,321 (5,827)	6	3,278	0.70	2,532	0.82	0.70
Plicatin	0	17.5	2.3 (3.8)	8	2.2	0.71	2.8	0.59	0.48

[a] Values are presented in parts per million. Plicatin reported as peak area ratio due to absence of an authentic standard for quantification. SD = standard deviation; PC = number of principal components used in the model; RMSECV = root mean standard error of cross validation; RMSEP = root mean standard error of prediction; RPE = relative prediction error.

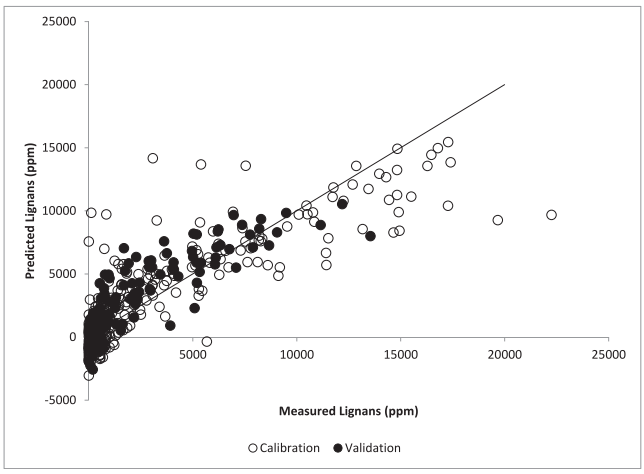

Figure 2.—Predicted concentration of lignans as a function of measured lignans.

prediction of decay resistance based on VIS/NIR spectra does not appear feasible.

The relationship between decay resistance and extractive concentrations was examined to determine whether measurement of any specific extractive or group of extractives could enable prediction of decay resistance. Correlations between fungal weight loss data and specific extractives or groups of extractives were very low (Table 3). Previous attempts to correlate extractives with decay resistance in laboratory tests using unleached, fresh wood blocks also found poor correlations but did conclude that samples with high concentrations of thujaplicins were more resistant to decay (DeBell et al. 1997). In the present work, leaching and potential biodegradation would have likely reduced the concentration of thujaplicins (Stirling and Morris 2011) and their influence on decay resistance. The poor correlations between weight losses and plicatic acid and plicatin concentrations contrast with the moderate correlations found in field tests (Morris and Stirling 2012). This may be due to

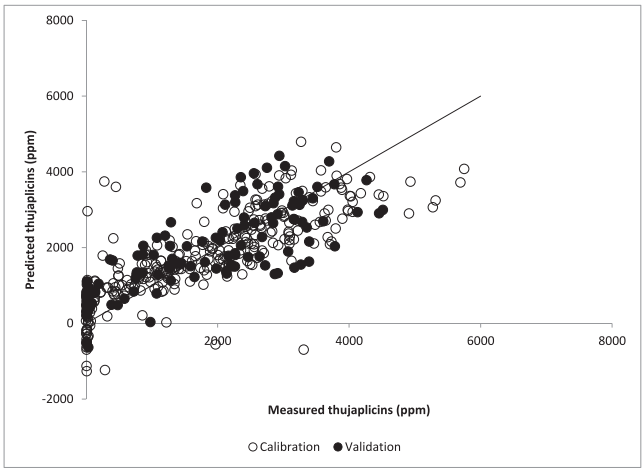

Figure 3.—Predicted concentration of thujaplicins as a function of measured thujaplicins.

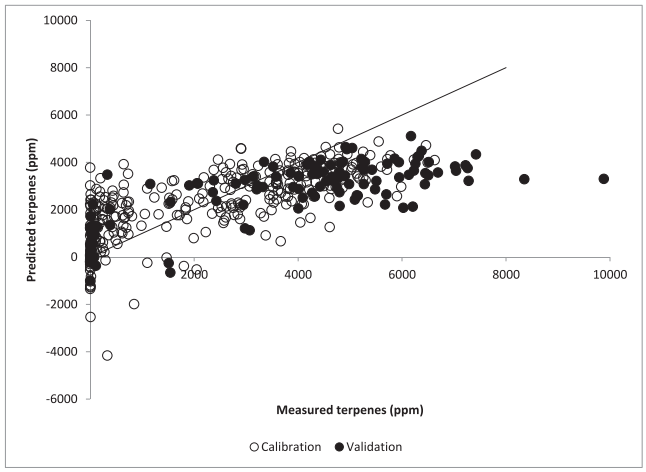

Figure 4.—Predicted concentration of terpenes as a function of measured terpenes.

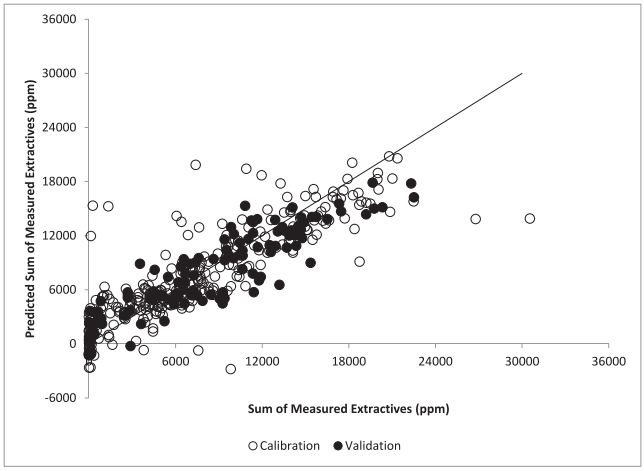

Figure 5.—Predicted sum of all measured extractives as a function of sum of all measured extractives.

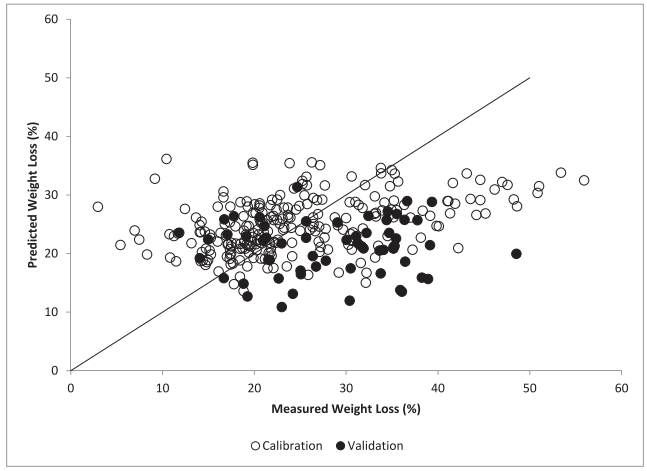

Figure 7.—Prediction of weight loss in blocks exposed to Coniophora puteana *from partial least squares models based on visible/near-infrared spectra.*

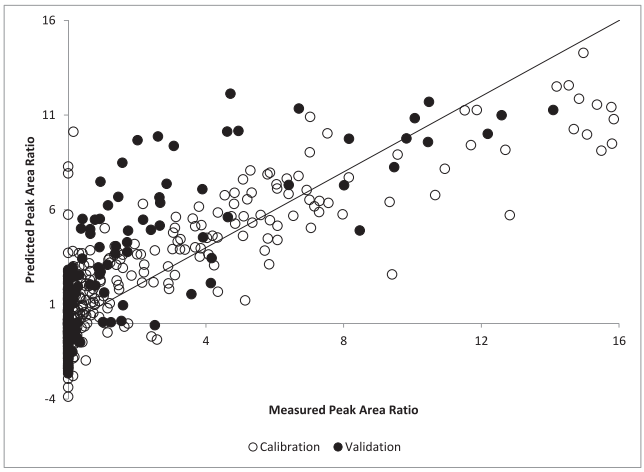

Figure 6.—Predicted peak area ratio of plicatin as a function of measured peak area ratio of plicatin.

different organisms causing decay in the field tests than those used in this laboratory test.

Correlations between color and decay resistance were also examined (Table 4). Lightness (L*) and yellowness (b*) were not significantly correlated with decay resistance, while there was a small but significant correlation between redness (a*) and decay resistance. This may suggest an association between decay resistance and the polyphenolic polymers associated with color in WRC (Kai and Swan 1990, Johansson et al. 2000).

Termites

The WRC blocks had an average weight loss of 27.9 percent and an average termite mortality of 6.1 percent (Table 2). There were wide ranges in weight loss and termite mortality, suitable for this correlational study. There were minor variations in weight loss between batches, as would be expected with this type of testing. Because nondurable controls were not included, and deviations from the standard method were made, these data should not be considered indicative of WRC's termite resistance in general.

VIS/NIR spectral data from batches 1 to 5 were used to develop models to predict weight loss. Correlations between VIS/NIR spectra and termite mortality were too weak for modeling. The developed model had moderate predictive ability (Fig. 8). It could be used as a screening tool, but would not be sufficiently accurate for phenotyping.

As with previous findings (Arango et al. 2006), there was a significant negative correlation between weight loss and termite mortality ($R = 0.61$, $P < 0.001$). None of the measured extractives were significantly correlated with weight loss or termite mortality ($P < 0.05$). These results are consistent with work by Taylor et al. (2006), which found poor correlations between individual known heartwood extractives and termite resistance. Analysis of these known extractives would therefore not be a suitable method for predicting termite resistance.

There was a small but significant ($R = 0.52$, $P < 0.001$) association between weight loss from *C. puteana* and weight loss from *C. formosanus*. This is consistent with Taylor et

Table 2.—Summary of decay and termite resistance and partial least squares model statistics using visible/near-infrared data.[a]

				Calibration			Validation		
Data set	Min.	Max.	Mean (SD)	PC	RMSECV	R^2	RMSEP	R^2	RPE
Decay, weight loss	3.0	55.9	25.6 (9.4)	3	8.8	0.17	14.2	0.07	−8.12
Termite, weight loss	3.6	54.8	27.9 (11.4)	6	8.1	0.51	5.6	0.75	0.76
Termite, mortality	0.5	43.2	6.1 (4.2)			Not modeled			

[a] Values are presented in percentages. SD = standard deviation; PC = number of principal components used in the model; RMSECV = root mean standard error of cross validation; RMSEP = root mean standard error of prediction; RPE = relative prediction error.

Table 3.—Correlations between decay and termite resistance and measured extractives.

	Weight loss (*Coniophoraputeana)*		Weight loss (*Coptotermes formosanus*)		Mortality (*Coptotermes formosanus*)	
Extractive	*R*	*P*	*R*	*P*	*R*	*P*
Plicatic acid	0.047	0.746	−0.065	0.652	0.022	0.882
Thujaplicatin methyl ether	0.120	0.407	−0.120	0.407	0.134	0.354
Lignans	0.062	0.669	−0.078	0.591	0.043	0.769
Alpha-thujaplicin	0.149	0.301	−0.232	0.105	0.144	0.320
Beta-thujaplicin	0.242	0.090	−0.016	0.910	0.098	0.500
Beta-thujaplicinol	0.037	0.798	−0.139	0.335	0.022	0.878
Gamma-thujaplicin	0.135	0.351	−0.033	0.818	0.096	0.508
Thujaplicins	0.175	0.223	−0.107	0.458	0.114	0.430
Thujic acid	0.107	0.458	0	1	0.115	0.425
Methyl thujate	0.058	0.689	0.069	0.634	−0.142	0.324
Terpenes	0.108	0.457	0.001	0.997	0.114	0.430
Total	0.119	0.411	−0.068	0.638	0.095	0.512
Plicatin	0.047	0.747	−0.090	0.536	0.148	0.306

Table 4.—Correlations between decay and termite resistance and colorimetric data.

	Weight loss from *Coniophora puteana*		Weight loss from *Coptotermes formosanus*		*Coptotermes formosanus* mortality	
Variable[a]	*R*	*P*	*R*	*P*	*R*	*P*
L*	0.25	0.080	0.39	0.006	−0.22	0.129
a*	−0.39	0.006	−0.69	0.000	0.57	0.000
b*	−0.06	0.688	0.18	0.208	−0.26	0.077

[a] L* = lightness on a scale from 0 to 100; a* = green (negative) and red (positive) coloration; b* = blue (negative) and yellow (positive) coloration.

al. (2006), who reported a similar association between weight loss from *C. formosanus* and weight loss from *P. placenta* in WRC. This suggests that some, but not all, of the factors associated with decay resistance are also associated with termite resistance.

Average color measurements from blocks in batches 3 to 5 were correlated with weight loss and termite mortality data (Table 3). L* and a* had significant associations with weight loss data, while only a* had a significant association with termite mortality. The negative correlation between weight loss and a*, and the positive correlation with termite mortality, suggests an association between red-colored wood and termite resistance. Heartwood color in WRC has been linked to polyphenolic lignan-based polymers (Kai and Swan 1990, Johansson et al. 2000). This association suggests a potential link between these incompletely characterized compounds and termite resistance in WRC. Despite this moderately strong correlation between weight loss, termite mortality, and a*, there is too much variability to reliably predict termite resistance from colorimetric data.

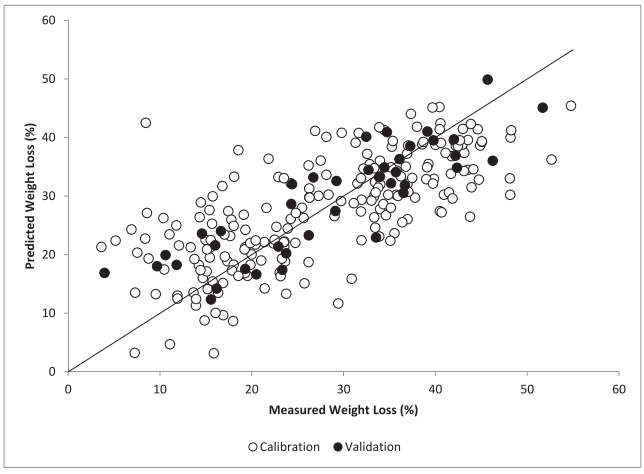

Figure 8.—Prediction of weight loss in blocks exposed to Coptotermes formosanus *from partial least squares models based on visible/near-infrared spectra.*

Red-colored heartwood in hinoki (*Chamaecyparis obtusa*) has been associated with resistance to *R. speratus* (Kijidani et al. 2012). Similar observations have also been made in teak (*T. grandis*). Lukmandaru (2011) found poor correlations between extractives fractions and resistance to *R. speratus,* while significant correlations were found with redness and color, which were associated with the presence of tannins, quinones, and polyphenols. Further work is needed to understand the associations between color and heartwood chemistry and termite resistance in naturally durable woods.

Conclusions

- PLS models based on VIS/NIR spectra had moderate predictive ability for lignans, plicatic acid, beta-thujaplicinol, and total extractives. Other extractives were poorly predicted.
- PLS models based on VIS/NIR spectra were not predictive of decay resistance.
- Decay resistance was not strongly associated with any measured extractive or with wood color.

- PLS models based on VIS/NIR spectra were moderately predictive of termite resistance.
- Termite resistance was moderately correlated with redness (a*).

Acknowledgments

FPInnovations would like to thank its industry members, Natural Resources Canada (Canadian Forest Service); the Provinces of British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, Nova Scotia, New Brunswick, and Newfoundland and Labrador, as well as the Government of Yukon for their guidance and financial support for this research.

The authors are grateful for assistance from John Russell (sourcing wood), Thanh Trung (spectral collection), Karen Leung (decay testing), Lisa McCuaig (extractives analysis), and Maria Aihara-Sasaki (termite testing).

Literature Cited

American Wood Protection Association (AWPA). 2009. Standard method of testing wood preservatives by laboratory soil-block cultures. Standard E10-09. AWPA, Birmingham, Alabama. 10 pp.

American Wood Protection Association (AWPA). 2012. Standard method for laboratory evaluation to determine resistance to subterranean termites. Standard E1-09. AWPA, Birmingham, Alabama. 9 pp.

Arango, R. A., F. Green III, K. Hintz, P. K. Lebow, and R. B. Miller. 2006. Natural durability of tropical and native woods against termite damage by *Reticulitermes flavipes* (Kollar). *Int. Biodeterior. Biodegrad*. 57(3):146–150.

ASTM International. 2005. Standard test method of accelerated laboratory test of natural decay resistance of woods. Standard D2017-05. ASTM International, West Conshohocken, Pennsylvania. 5 pp.

Baillères, H., F. Davrieux, and F. Ham-Pichavant. 2002. Near infrared analysis as a tool for rapid screening of some major wood characteristics in a eucalyptus breeding program. *Ann. Forest Sci*. 59:479–490.

Barton, G. M., B. F. MacDonald, and T. S. Sahota. 1972. Juvenile hormone-like activity of Thujic acid, an extractive of western red cedar. *Can. Forest Serv. Bi-monthly Res. Notes* 28(4):22–23.

Carter, F. L. and R. V. Smythe. 1974. Feeding and survival responses of *Reticulitermes flavipes* (Kollar) to extractives of wood from 11 coniferous genera. *Holzforschung* 28(2):41–45.

Cartwright, K. S. G. 1941. The variability in resistance to decay of the heartwood of home-grown western red cedar (*Thuja plicata* D. Don) and its relation to position in the log. *Forestry* 15(1):65–75.

Chedgy, R. J., Y. W. Lim, and C. Breuil. 2009. Effects of leaching on fungal growth and decay of western redcedar. *Can. J. Microbiol*. 55:578–586.

Daniels, C. R. and J. H. Russell. 2007. Analysis of western redcedar (*Thuja plicata* Donn) heartwood components by HPLC as a possible screening tool for trees with enhanced natural durability. *J. Chromatogr. Sci*. 45:281–285.

DeBell, J. D., J. J. Morrell, and B. L. Gartner. 1997. Tropolone content of increment cores as an indicator of decay resistance in western redcedar. *Wood Fiber Sci*. 29(4):364–369.

DeBell, J. D., J. J. Morrell, and B. L. Gartner. 1999. Within-stem variation in tropolone content and decay resistance of second-growth western redcedar. *Forest Sci*. 45(1):101–107.

Englerth, G. H. and T. C. Scheffer. 1955. Tests of decay resistance of four western pole species. *J. Forestry* 53:556–561.

European Committee for Standardization (CEN). 1994. Durability of wood and wood-based products—Natural durability of solid wood—Part 2: Guide to natural durability and treatability of selected wood species of importance to Europe. EN350-2. CEN, Brussels.

Flæte, P. O., G. Alfredsen, and F. G. Evans. 2011. Natural durability of wood tested in different environments in Northern Europe. Document No. IRG/WP/11-10747. International Research Group on Wood Protection, Stockholm. 8 pp.

Flæte, P. O. and E. Y. Haartveit. 2004. Non-destructive prediction of decay resistance of *Pinus sylvestris* heartwood by near infrared spectroscopy. *Scand. J. Forest Res*. 19(6):55–63.

Freitag, C. M. and J. J. Morrell. 2001. Durability of a changing western redcedar resource. *Wood Fiber Sci*. 33:69–75.

Gierlinger, N., D. Jacques, M. Schwanninger, R. Wimmer, B. Hinterstoisser, and L. E. Pâques. 2003. Rapid prediction of natural durability of larch heartwood using Fourier transform near infrared spectroscopy. *Can. J. Forest Res*. 33:1727–1736.

Indrayani, Y., T. Yoshimura, Y. Yanase, and Y. Imamura. 2007. Feeding responses of the western dry-wood termite *Incisitermes minor* (Hagan) (Isoptera: Kalotermitidae) against ten commercial timbers. *J. Wood Sci*. 53:239–248.

Johansson, C. I., J. N. Saddler, and R. P. Beatson. 2000. Characterization of the polyphenolics related to the colour of western red cedar (*Thuja plicata* Donn) heartwood. *Holzforschung* 54:246–254.

Johnson, E. L. and A. J. Cserjesi. 1980. Weathering effect on thujaplicin concentration in western redcedar shakes. *Forest Prod. J*. 30(6):52–53.

Kai, Y. and E. P. Swan. 1990. Chemical constituents contributing to the color of western red cedar heartwood. *Mokuzai Gakkaishi* 36(3):218–224.

Kijidani, Y., N. Sakai, K. Kimura, Y. Fujisawa, Y. Hiraoka, J. Matsumura, and S. Koga. 2012. Termite resistance and color of heartwood of hinoki (*Chamaecyparis obtusa*) trees in 5 half-sib families in a progeny test stand in Kyushu, Japan. *J. Wood Sci*. 58(6):471–478.

Kirker, G. T., A. B. Blodgett, R. A. Arango, P. K. Lebow, and C. A. Clausen. 2013. The role of extractives in naturally durable wood species. *Int. Biodeterior. Biodegrad*. 82:53–58.

Lukmandaru, G. 2011. Variability in the natural termite resistance of plantation grown teak wood and its relations with wood extractive content and color properties. *J. Forestry Res*. 8(1):17–31.

MacLean, H. and J. A. F. Gardner. 1956. Distribution of fungicidal extractives (thujaplicin and water soluble phenols) in western red cedar heartwood. *Forest Prod. J*. 6(12):510–516.

Mannesmann, R. 1973. Comparison of twenty-one commercial wood species from North America in relation to feeding rates of the Formosan termite, *Coptotermes formosanus* Shiraki. *Mater. Org*. 8(2):107–120.

Meder, R., A. Thumm, and H. Bier. 2002. Veneer stiffness predicted by NIR spectroscopy calibrated using mini-LVL test panels. *Holz Roh-Werkst*. 60(3):159–164.

Morales-Ramos, J. A. and M. G. Rojas. 2001. Nutritional ecology of the Formosan subterranean termite (Isoptera: Rhinotermitidae): Feeding response to commercial wood species. *J. Econ. Entomol*. 94(2):516–523.

Morris, P. I., J. K. Grace, and K. Tsunoda. 2009. Field testing of wood preservatives. XVIII. Performance of borate-treated wood against subterranean termites. *Proc. Can. Wood Preserv. Assoc*. 30:272–295.

Morris, P. I., J. Ingram, G. Larkin, and P. Laks. 2011. Field tests of naturally durable species. *Forest Prod. J*. 61(5):344–351.

Morris, P. I. and R. Stirling. 2012. Western red cedar extractives associated with durability in ground contact. *Wood Sci. Technol*. 46(5):991–1002.

Niamké, F., N. Amusant, A. Kadio, M. Thevenon, S. Nourissier, A. Adima, C. Jay-Allemand, and G. Chaix. 2014. Rapid prediction of phenolic compounds as chemical markers for the natural durability of teak (*Tectona grandis* Linn f.) heartwood by near infrared spectroscopy. *J. Near Infrared Spectrosc*. 22:35–43.

Ohmura, W., I. Momohara, M. Kiguchi, T. Yoshimura, Y. Takematsu, H. Gensai, T. Nomura, T. Kaneda, M. Saegusa, S. Maeda, and M. Tanikawa. 2011. Anti-termite performance of Japanese and foreign timber species under different degradation environments. *Mokuzai Gakkaishi* 57(1):26–33.

Poke, F. S. and C. A. Raymond. 2006. Predicting extractives, lignin, and cellulose contents using near infrared spectroscopy on solid wood in *Eucalyptus globulus*. *J. Wood Chem. Technol*. 26(2):187–199.

Rennerfelt, E. 1948. Thujaplicin, a fungicidal substance in the heartwood of *Thuja plicata*. *Physiol. Plant*. 1:245–254.

Roff, J. W. and J. M. Atkinson. 1954. Toxicity tests of a water-soluble phenolic fraction (thujaplicin-free) of western red cedar. *Can. J. Bot*. 32:308–309.

Roff, J. W. and E. I. Whittaker. 1959. Toxicity tests of a new tropolone, beta-thujaplicinol (7-hydroxy-4-isopropyltropolone) occurring in western red cedar. *Can. J. Bot*. 37:1132–1134.

Russell, J. H. and C. R. Daniels. 2010. Variation in western redcedar heartwood extractives. *In:* A Tale of Two Cedars: International Symposium on Western Redcedar and Yellow-Cedar. C. A. Harrington (Ed.). General Technical Report PNW-GTR-828. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon, pp. 83–86.

Rust, M. K. and D. A. Reierson. 1977. Using wood extracts to determine the feeding preferences of the western drywood termite, *Incisitermes minor* (Hagan). *J. Chem. Ecol*. 3(4):391–399.

Scheffer, T. C. 1957. Decay resistance of western redcedar. *J. Forestry* 55(6):434–442.

Standards Australia. 2005. Timber—Natural durability ratings. Australian Standard 5604. Standards Australia, Sydney. 24 pp.

Stirling, R. 2010. Residual extractives in western red cedar shakes and shingles after long-term field testing. *Forest Prod. J*. 60(4):353–356.

Stirling R., J. E. Clark, C. R. Daniels, and P. I. Morris. 2007. Methods for determining the role of extractives in the natural durability of western red cedar heartwood. Document No. IRG/WP/07-20356. International Research Group on Wood Protection, Stockholm. 12 pp.

Stirling, R. and P. I. Morris. 2006. The influence of extractives on western red cedar's equilibrium moisture content. Document No. IRG/WP 06-40331. International Research Group on Wood Protection, Stockholm. 12 pp.

Stirling, R. and P. I. Morris. 2010. Reducing depletion of western redcedar extractives from wood in service. *In:* A Tale of Two Cedars: International Symposium on Western Redcedar and Yellow-Cedar. C. A. Harrington (Ed.). General Technical Report PNW-GTR-828. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon. pp. 87–92.

Stirling, R. and P. I. Morris. 2011. New perspectives on the role of extractives in the durability of western redcedar. *Proc. Can. Wood Preserv. Assoc*. 32:12 pp.

Su, N.-Y. and M. Tamashiro. 1986. Wood-consumption rate and the survival of the Formosan subterranean termite (Isoptera: Rhinotermitidae) when fed one of six woods used commercially in Hawaii. *Proc. Hawaiian Entomol. Soc*. 26: 109–113.

Sykacek, E., N. Gierlinger, R. Wimmer, and M. Schwanninger. 2006. Prediction of natural durability of commercial available European and Siberian larch by near-infrared spectroscopy. *Holzforschung* 60:643–647.

Taylor, A. M., C. Freitag, E. Cadot, and J. J. Morrell. 2008. Potential of near infrared spectroscopy to assess hot-water-soluble extractive content and decay resistance of a tropical hardwood. *Holz Roh-Werkst*. 66:107–111.

Taylor, A. M., B. L. Gartner, J. J. Morrell, and K. Tsunoda. 2006. Effects of heartwood extractive fractions of *Thuja plicata* and *Chamaecyparis nootkatensis* on wood degradation by termites or fungi. *J. Wood Sci*. 52:147–153.