ASSESSING WOOD QUALITY OF BORER-INFESTED RED OAK LOGS WITH A RESONANCE ACOUSTIC TECHNIQUE

*Xiping Wang**†

Senior Research Associate
Natural Resources Research Institute
University of Minnesota Duluth
Duluth, MN 55811
and
USDA Forest Service
Forest Products Laboratory
Madison, WI 53726-2398

Henry E. Stelzer

Associate Professor
Forestry Department
University of Missouri
Columbia, MO 65211

Jan Wiedenbeck†

Project Leader
USDA Forest Service
Northern Research Station
Princeton, WV 24740

Patricia K. Lebow

Mathematical Statistician

Robert J. Ross†

Project Leader
USDA Forest Service
Forest Products Laboratory
Madison, WI 53726-2398

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Abstract. Large numbers of black oak (*Quercus velutina* Lam.) and scarlet oak (*Quercus coccinea* Muenchh.) trees are declining and dying in the Missouri Ozark forest as a result of oak decline. Red oak borer-infested trees produce low-grade logs that become extremely difficult to merchandize as the level of insect attack increases. The objective of this study was to investigate the use of a resonance-based acoustic technique to evaluate the wood quality of infested red oak logs before processing as measured by grade, type and location of defects, and mechanical properties of the resulting boards. Principal component and canonical correlation analyses revealed that relationships do exist between log acoustic measurement and board grade yield, and between a linear combination of log acoustic velocity and diameter at breast height and a linear combination of board defect measurements. Although the acoustic technique was found capable of assessing wood quality at a stand level, the major advantage of the technique lies in segregating logs within the stand.

Keywords: Acoustic velocity, logs, defects, grade yield, mechanical properties, oak decline, red oak, red oak borer.

* Corresponding author: xwang@fs.fed.us
† SWST member

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INTRODUCTION

The red oak borer, *Enaphalodes rufulus* (Haldeman) Coleoptera: Cerambycidae, is a wood-boring insect that occurs at low population levels throughout a wide range of deciduous forests in North America (Donley and Acciavatti 1980; Donley and Rast 1984; Hay 1974). From 1999 to 2005, the forests of the Ozark Mountains in Arkansas and Missouri experienced a remarkable outbreak of this normally endemic insect species. This unprecedented outbreak has been linked with a widespread oak decline in the two-state region (Starkey et al 2000; Stephen et al 2001).

Most oaks (*Quercus* spp.) in eastern North America are attacked by the borer. The most common hosts are members of the red oak subgenus *Erythrobalanus*: northern red oak (*Q. rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.). Economic loss occurs when the borer tunnels and causes subsequent wood overgrowths in attacked trees that appear on the grading surfaces of boards and veneer. Wood-inhabiting insects such as carpenter worms, timber worms, and carpenter ants use red oak borer tunnels to gain entry into oaks. These other pests extend and increase the damage. Decay organisms also gain entry into oak heartwood through borer tunnels.

The loss in grade can amount to 40% of the current tree value, which, at today's prices, is about $45 per cubic meter for factory-grade lumber in terms of reduced quality caused by larval tunnels. About 38% of the oak wood used for lumber, cooperage, and veneer in the eastern United States is affected (Donley and Acciavatti 1980).

If the extent of damage is too severe, the most cost-effective decision often would be to leave the tree in the woods rather than harvest and process it. However, this decision is usually made after considerable logging costs have been incurred. Technologies are needed in both the forest and sawmill to quantify wood-borer damage in affected trees or logs suspected of having excessive infestation. With information on the extent of damage, better decisions can be made in both managing the forest stand and using individual trees and logs.

Acoustic velocity is a nondestructive measure that has been proved to be related to the basic wood and fiber properties such as stiffness, density, microfibril angle, and so on (Wang et al 2001, 2004; Carter et al 2005). It has also been recognized as a predicting parameter for wood deterioration caused by any wood decay mechanism (Ross et al 2005). For red oak trees that have oak decline, physical damages such as worm holes, grub holes, and decay are the typical symptoms associated with the borer infestation. It is possible that these physical and chemical changes, on both a macro- and microstructural level, could affect the acoustic wave properties in trees and logs and the acoustic measures be effective in assessing the potential quality of the wood before logs are processed.

The objective of this study was to investigate the use of a resonance acoustic technique to nondestructively assess the extent of borer infestation in logs affected by oak decline and evaluate the grade yield and mechanical properties of the boards obtained from those logs.

MATERIALS AND METHODS

Log Samples

The sample logs for this study were part of a larger study to assess the potential use of small-diameter (15 – 30 cm, at 1.4 m above ground line) trees for flooring, pallets, and industrial blocking. In each of 10 stands, 100 trees were selected that represented the species and diameter distribution. The sample trees were then harvested and the tree-length stems were delivered to the mill yard where each stem was cut into 2.4 to 3.0 m long logs and numbered. As a result of oak borer infestation being more problematic in the red oak subgroup and the higher incidence of attack on the more xeric sites, only red oak species from the four south- and west-facing stands (designated as Stands 1, 2, 3, and 4) were used in the acoustic study, resulting in a total of 400 butt logs as samples, 100 from each stand.

Log Acoustic Measurements

Acoustic wave data were obtained from each butt log using a Director HM200™ resonance acoustic tool (Fiber-Gen Inc, Auckland, New Zealand). The acoustic signal was immediately processed using a Fast Fourier Transformation program (Harris et al 2002) and the acoustic velocity determined from:

$$C_L = \frac{2f_n L}{n} \tag{1}$$

where C_L is acoustic velocity of logs (m/s), f_n the natural frequency of the n^{th} harmonic of an acoustic wave signal (Hz), and L the log length (end-to-end) (m).

Because the data were collected not long after harvesting, the log acoustic velocity in this study refers to the green condition. To check the moisture levels in the butt logs, three butt logs were randomly selected from each stand and one 25 mm thick disc was cut from each log. The initial (green) weights of the moisture samples were obtained immediately after cutting from the logs. Oven-dry weights were later obtained at the laboratory and the MC of each disc was determined in accordance with the ASTM Standard D4442-92 (ASTM 2003a).

Mill Process

Being part of the larger small-tree utilization study, the butt logs for this acoustic study were stockpiled until all logs could be processed. Before processing, a subsample of 40 logs (10 from each stand) was randomly selected and set aside for characterizing the borer damage and determining mechanical properties of the resulting boards. The remaining 360 butt logs were sawn into 25 mm thick (4/4) boards, targeting wood flooring products. The boards from each log were kept together in a stack through edging and grading so that each board could be associated with the appropriate log number. For a variety of reasons (eg lost, illegible, and sawn-through tags), lumber grade data were collected on 333 of the 360 (93%) butt logs. The analysis assumes that omission of a log resulting from loss of identity was a random event.

All boards were graded according to the following local mill (Canoak, Inc, Salem, MO) grades:

Select: clear face on both sides with no knots or defects;
No. 1: clear face on one side with less than 20% knots or defects on the second face;
No. 2: clear face on one side with greater than 20% but less than 40% knots or defects on the second face;
No. 3: no clear faces with less than 40% knots or defects on either side; and
Pallet: no clear faces with greater than 40% knots or defects on both sides.

Generally, the local mill sells all Select-grade boards as molding or cabinet stock and uses No. 1, 2, and 3 grade boards in the flooring operation. Pallet-grade material is sold for pallet and industrial uses.

Mapping and Digitizing Board Defects

The primary defects associated with the borer infestation included decay, incipient decay, grub holes, shot worm holes, pin worm holes, sap stain, and mineral streak. Therefore, these defect types were used to characterize the red oak boards. The description of these defects is listed in Table 1.

The random subsample of 40 logs was sawn into 50 mm thick (8/4) boards. A total of 140 boards were recovered and identified by log. These boards were shipped to the USDA Forest Products Laboratory (FPL) in Madison, WI, and kiln-dried to a target MC of 12%. The boards were then visually inspected at the USFS Northern Research Station in Princeton, WV, where the defects on each board were digitally mapped using an *x-y* coordinate system and a digitizing unit adapted for lumber (Anderson et al 1993).

Characterization of defect information consisted of pairs of *x-y* coordinates on a grid

Table 1. *Description of defects used in evaluating study boards.*

Defect type	Defect code	Description
Decay	DECAY	The stage of decay in which destruction is readily recognized; wood has become punky, soft, and spongy
Incipient decay	INDEC	The early stage of decay that has not proceeded far enough to soften wood
Grub hole	GRUB	Diameter 6.4 mm and over
Shot worm hole	SHOT	Diameter between 1.6 and 6.4 mm
Pin worm hole	PIN	Diameter 1.6 mm or less
Stain	STAIN	Discoloration and initial evidence of decay
Mineral streak	MINER	Discoloration of undetermined cause

corresponding to the lower left (LY, LX) and upper right (UY, UX) corners of the smallest rectangle completely enclosing each defect. The grid system and a unique origin at (0, 0), which is the same physical corner of the board regardless of the face being mapped, were used to map all natural defects on each face of each board. Because boards were of different widths, and hence different surface areas, defect information was adjusted to a relative surface area basis.

In this process, each defect was described by defect type codes, defect size codes, coordinates of defect location on the board rectangle, and faces on which the defect occurred. In encoding defects, some defects will fit more than one description because different characteristics are grouped too tightly to separate with multiple rectangles. In this case, the defect was encoded based on the dominant defect.

Mechanical Testing of Boards

After mapping and digitizing the board defects, all boards sawn from the log subsamples were mechanically tested to determine stiffness and strength. The boards were first E-rated using a transverse-vibration technique in accordance with the ASTM standard D 6874-03 (ASTM 2003b). The following formula was used to calculate modulus of elasticity (MOE) from the measured oscillation in the fundamental mode:

$$MOE_{tv} = \frac{f_0^2 ws^3}{k_d Ig} \qquad (2)$$

where MOE_{tv} = transverse vibration modulus of elasticity (MPa), s = span (mm), w = weight of board (N), f_0 = fundamental frequency of oscillation (Hz), I = board moment of inertia (mm^4), g = acceleration resulting from gravity (9807 mm/s^2), and k_d = constant for free vibration of a simply supported beam (2.47).

After E-rating, static bending tests were performed on all full-sized boards according to ASTM standard D 198-02 (ASTM 2003c). The boards were loaded edgewise and tested to failure using center-point loading with a span of 2.24 m. The exact dimension of each board was measured and the maximum load was recorded for each testing. The modulus of rupture (MOR) was calculated based on the following formula:

$$MOR = \frac{Pl}{bh^2} \qquad (3)$$

where P = maximum transverse load on board (N), l = span of board (mm), b = thickness of board (mm), and h = depth of board (mm).

Data Analysis

Identification of board defects associated with borer infestation. The mapping and digitizing process for defect characterization permits defect-type summaries to be generated for the boards cut from the log subsamples (40 butt logs). For differentiating the particular defects associated with the borer infestation in Missouri red oak logs, these summarized defect results were compared with the 1998 red oak data bank (Gatchell et al 1998), which was generated from the normal red oak boards. The significant difference between the distributions for the board samples used in this study and the data bank boards would indicate the defect types that are most likely associated with the borer infestation that occurs in the majority of trees with oak decline.

Determining relationships between log acoustic velocity and board grade yield. One way to quantify the effectiveness of acoustic measurement as a quality criterion is to determine the relationships between acoustic velocity of the logs and the grade levels of the boards cut from the logs. For this purpose, we pooled the log data of all four stands (360 butt logs) and divided them into six classes based on acoustic velocity of the logs with the following acoustic velocity ranges:

G1: less than 2.6 km/s;
G2: 2.6 – 2.8 km/s;
G3: 2.8 – 3.0 km/s;
G4: 3.0 – 3.2 km/s;
G5: 3.2 – 3.4 km/s; and
G6: greater than 3.4 km/s.

The acoustic velocity class of the logs was then associated with the board grade levels as determined based on the grading rules of the local mill: Select, No. 1, No. 2, No. 3, and Pallet.

Determining relationships between log acoustic data and defect/property measures of boards. Additonally, relationships between the acoustic values for logs and the defect and mechanical property measurements for boards were evaluated using the methods of principal component analysis (PCA) and canonical correlation analysis (CANCOR, also sometimes referred to in the literature as CCA) (Mardia et al 1979; Johnson and Wichern 2002). Methods for multivariate modeling and data reductions are numerous, often relying heavily on the objectives of the particular study at hand. For this particular data, various stages of data reduction are possible that could result in different interpretations. Because boards were of different widths, and hence different surface areas, defect information was adjusted to a relative surface area basis. Second, the correlation-based methods can be applied to the data at the board level (this is referred to as the log-board data). Because there are typically multiple boards from each log, board measurements can be combined to give an overall assessment for each defect type within each log and then correlation-based methods can be applied to this reduced data (referred to as log-level data). This primarily removes the variation between boards within logs. Evaluation of both sets of data will help with the characterization of within- and between-log variations.

PCA offers data exploration as well as the possibility of data reduction by finding linear combinations of the original variables with relative large (or small) variability and transforming correlated variables into uncorrelated ones. Ideally, the data are from a multivariate normal population, yet even in situations such as this with semicontinuous, nonnormal data, useful information is possible. CANCOR similarly offers data exploration and data reduction, but between two groups of variables by finding pairs of linear combinations of each of the two groups that are maximally correlated such as between the defect measurements and the nondestructive measurements of logs. CANCOR has the feature that if one set of the variables contains a single variable, it reduces to the typical multivariate linear regression.

Following Mardia et al (1979), stepwise tests were used to evaluate the significance of the canonical correlations. For the CANCOR analysis, the relative clear area variable was excluded in the calculations, because it is essentially a linear combination of the original defect variables. CANCOR, unlike PCA, has an invariance property such that standardization does not affect the canonical correlations and the nonstandardized canonical correlation vectors can be derived from the standardized vectors.

Analysis was carried out with SAS (SAS Institute, Inc 2004), S-PLUS (Venables and Ripley 1997; Insightful Corporation 2001), and R (Fox 2002; The R Foundation for Statistical Computing 2004) statistical software packages. Relationships between variables were examined graphically with Corrgrams (Friendly 2002). PCA and CANCOR were done in S-PLUS, whereas the CANCOR intensity plots were done in R.

RESULTS AND DISCUSSION

Log Acoustic Velocity and Grade Yield by Stands

Table 2 summarizes the general statistics of tree diameter (DBH) and log acoustic velocity on a stand basis. The logs were in the green condition during cutting and measurement processes. The MCs of the disc samples indicated a moisture range of 48 – 68% for the logs, well above the FSP.

The velocity distribution patterns of the four stands were similar and appear to be normally distributed (Fig 1). The observed variation in acoustic velocity within each stand implies a wide range of wood properties and quality. If a direct relationship exists between acoustic velocity and log quality as a result of borer-related defects, then acoustic measurement could be used to segregate good, healthy stems/logs from severely infested stems/logs. Analysis of variance did reveal a significantly lower mean acoustic velocity in Stand 3 and there was a higher percentage of boards in the lower-quality classes (Table 3).

Log Acoustic Velocity Compared with Board Grades

Figure 2 shows how the board grade yield changes as the log acoustic velocity changes. There is a direct relationship between board yield and log acoustic velocity in the first three grades (Select, No. 1, No. 2). As log velocity increased, yield increased. On the other hand, the board yield of the lowest grade decreased significantly as the log velocity increased. These two opposite velocity grade trends reflected distinct differences between good-quality boards with less or no borer infestation and poor-quality boards with severe borer attacks. According to the grading rules, the higher-grade boards must have one or two clear faces with no or few defects, suggesting that they were not affected by the borer infestation or had only minor infestation. Pallet stocks, on the other hand, are ones that have poor quality with severe defects. About 45% of the total boards were in this grade. This reflects the quality problem associated with the oak decline in the region. The velocity-grade trends suggest that log acoustic velocity could be effectively used to segregate severely infested stems/logs from good stems/logs.

Defect Prevalence and Distribution

The defect mapping of the 140 boards cut from the 40-log subsample reveal that these boards contain a wide range of severe defects. The most prevalent defects based on the percentage of boards affected were unsound knots (91%), bark pockets (89%), wane (82%), grub holes (71%), and splits (52%) (Table 4). Forty-eight of the 140 boards contained pith, an indication that a significant fraction of these boards were removed from the inner, lower-quality parts of the log. On the other hand, the fact that bark pocket and wane, defects encountered in boards removed from the outer sections of the log, were the second and third most prevalent defects indicates that a high proportion of these boards contained outer wood. In fact, most of these boards contained both wood from the core

Table 2. *DBH of the red oak tree samples and acoustic velocity of the butt logs cut from the trees.*

	DBH of tree samples (cm)				Acoustic velocity of logs (km/s)			
Stand number	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
1	20.8	2.45	15.2	25.4	3.07	0.264	2.54	3.63
2	20.5	4.10	12.7	30.5	2.99	0.317	2.15	3.76
3	21.5	4.29	15.2	30.5	2.89	0.237	2.07	3.26
4	21.1	4.53	12.7	30.5	3.01	0.340	2.04	3.84

DBH, diameter at breast height of standing trees; SD, standard deviation.

and periphery because these were butt logs from small-diameter trees.

The second right-most column in Table 4 shows defect distribution for the 239 No. 3A Common boards in the 1998 red oak data bank (Gatchell et al 1998). The differences between the distributions for the Missouri and data bank boards are revealing. There are several types of defects that are found on at least 20% more of the boards sawn from the Missouri oak compared with the No. 3A Common lumber in the 1998 data bank (Table 4). Defect types that are listed in italics in Table 4 are especially common in the Missouri lumber: grub holes (greater than 6.4 mm dia), shot worm holes (6.4 mm dia or less), pin worm holes (1.6 mm dia or less), decay, incipient decay, mineral streak, and wane. All of these defect types, except for wane, are likely associated with borer infestation that occurs in the majority of trees with oak decline.

Mechanical Properties of Boards

The MOE and MOR of the boards cut from the 40-log subsample are summarized in Table 5. The general statistical measures are shown on

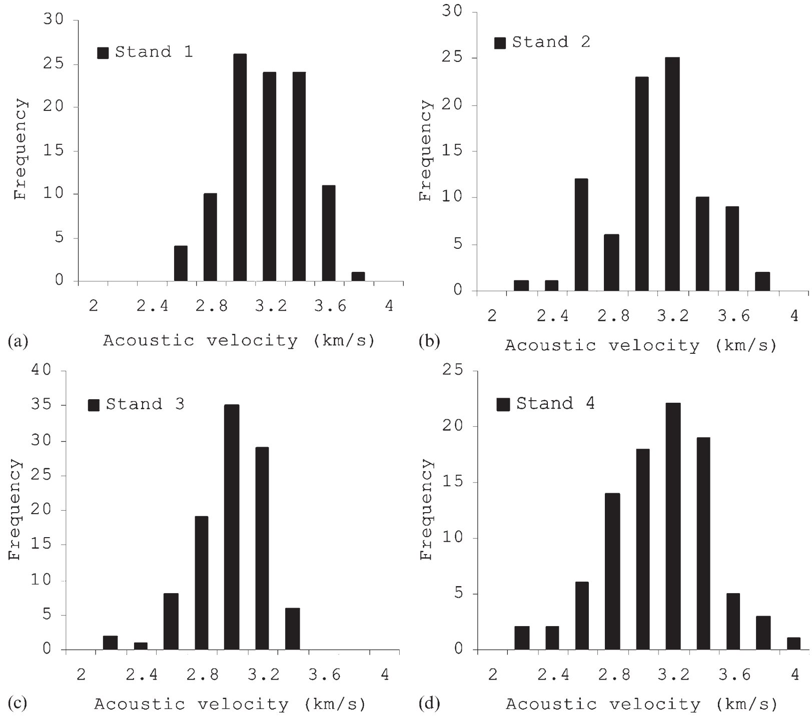

Figure 1. Distribution of log acoustic velocity within each stand.

Table 3. *Grade yields of the Missouri red oak boards sawn from the butt logs removed from four oak decline-affected stands.*[a]

	Board grade yield (%)					Grouped grade yield (%)	
Stand number	Select	No. 1	No. 2	No. 3	Pallet	No. 2 and better	No. 3 and Pallet
1	1.3	2.3	18.6	33.5	44.2	22.3	77.7
2	4.5	8.9	14.3	30.0	42.3	27.7	72.3
3	0.5	5.0	10.5	38.5	45.5	16.0	84.0
4	0.8	6.6	19.6	27.7	45.4	26.9	73.1

[a] Board grade yield is based on the local mill grading criteria used in the production operations (Canoak Inc, Salem, MO).

both stand and overall basis. For all stands combined, MOE ranged from 3.65 – 18.27 GPa with a mean of 9.51 GPa; MOR ranged from 13.8 – 114.9 MPa with a mean of 62.1 MPa. It is evident that the MOE and MOR of the borer-infested red oak boards are significantly lower than values given in the Wood Handbook (MOE: 11.3 GPa for black oak, 13.2 GPa for scarlet oak; MOR: 96 MPa for black oak, 120 MPa for scarlet oak) (Forest Products Laboratory 1999). Depending on specific species (black oak or scarlet oak), red oak boards tested in this study may show 15.8 – 28% reduction in MOE and 35.3 – 48.3% reduction in MOR as compared with the Wood Handbook values. Although the material source itself, characterized as small-diameter logs, could be part of the reason responsible for this property reduction, the extremely low values in the lower range of MOE and MOR in Table 5 imply that the physical and chemical damages caused by oak decline are the main factors contributing to this significant property loss.

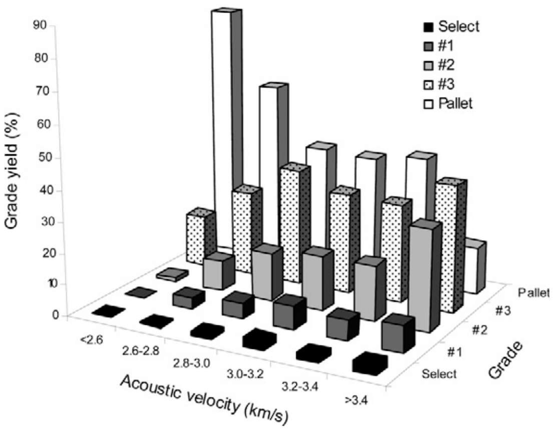

Figure 2. Relationship between log acoustic velocity and board grade yield.

Because only 10 butt logs were selected from each stand for mechanical testing, comparison of mechanical properties among stands may not be meaningful. Nevertheless, the board samples from Stand 3 did show much lower property

Table 4. *Defect summary of the Missouri red oak boards sawn from the log subsamples and defect percentages for the No. 3A Common boards in the 1998 data bank.*[a]

	Missouri red oak board defect summary					
Type of defect	Total number of defects on all boards	Average defect size (cm^2)	Number of boards affected	Percent of boards affected	Percent of boards affected in 1998 data bank	Percentage difference in defect distribution[b]
Unsound knot	1185	4.58	128	91	83	8
Bark pocket	1006	10.58	125	89	78	11
Wane	1612	44.32	115	82	47	35
Grub hole	455	63.10	99	71	28	43
Split	443	11.87	73	52	47	5
Decay	159	237.68	55	39	13	26
Mineral streak	199	90.19	55	39	0	39
Pin worm hole	369	6.19	53	38	6	32
Sound knot	96	1.55	51	36	23	13
Pith	188	63.42	48	34	36	−2
Shot worm hole	83	3.16	43	31	8	23
Incipient decay	106	99.55	38	27	0	27
Pith-related defects	352	46.19	37	26	34	−8
Shake	142	178.13	34	24	12	12

[a] Gatchell et al 1998.
[b] Positive numbers indicate that more of the lumber sawn from the Missouri red oak subsamples contains the listed defect than does the board in the 1998 red oak data bank.

Table 5. *Mechanical properties of the red oak boards cut from log subsamples.*[a]

	MOE_{tv} (GPa)				MOR (MPa)			
Stand number	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
1	9.91	2.290	5.96	16.27	62.5	17.48	20	91.4
2	9.94	2.357	6.27	18.27	65.3	22.55	19.4	114.9
3	8.90	2.717	3.65	15.24	60.2	19.70	13.8	101.1
4	9.26	3.177	4.48	15.44	60.1	24.13	23.2	103.6
All stands	9.51	2.668	3.65	18.27	62.1	21.17	13.8	114.9

[a] MOE_{tv}, modulus of elasticity determined using transverse vibration; MOR, modulus of rupture determined using edgewise static bending test; SD, standard deviation.

values than the other three stands, which is in agreement with acoustic and grade yield data.

Log Acoustic Velocity Compared with Defect Prevalence and Mechanical Properties of the Boards

A Corrgram for the log-level data is given in Fig 3. This is a visual rendering of the correlation matrix of the log-level data with the lower triangle giving the estimated correlations. The ordering of variables is based on an angular ordering of the eigenvectors (Friendly 2002), which tends to cluster the variables into associated groups. From this figure there appears to be three to five groups of variables (GRUB, TOTAL, SHOT, PIN), (CLEAR, MOEV, C, MOR), (STAIN), (DBH), and (MINER, INDEC, OTHER, DECAY). Those variables within a group tend to be positively associated with each other, whereas they tend to have either no or negative relationships with the other groups. For example, the strength and acoustic measurements appear to be positively associated but negatively related to the group with the MINER, INDEC, OTHER, and DECAY variables.

Figure 4(a–c) displays a portion of the PCA on the log-level data. Figure 4(a) is a principal component biplot; it combines a plot of the first two eigenvector loadings with the plot of the first two principal components. The vectors in the plot represent each variable's loading on the first and second eigenvectors, whereas the numbers in the plot are the log label plotted at the log's values for the first and second components, respectively. This plot reaffirms the interpretation of Fig 3 with four groupings of the original variables (by the vectors). Figure 4(b) displays the most prominent eigenvector loadings for the first five components (the first two correspond to the vectors in the biplot). Finally, the screen plot in Fig 4(c) gives the relative contribution to overall variation for each component.

Based on PCA, the first component appears to differentiate strength, acoustic measurement, and relative clear area to the group of defects, including mineral, incipient decay, decay, and other defects. This first component explains 29% of the total variation (of the correlation matrix) and represents the linear combination that explains the maximum contribution to the correlation matrix. The second principal component, orthogonal to the first, differentiates DBH with the grub holes, shot worm holes, and total defect count variables and explains an additional 16%. The remaining components gradually explain further variation in the data. When the log-board data were examined, the loadings for the first two components (ie the first two eigenvectors) and their contributions to the overall correlation (ie eigenvalues) were similar but then diverged afterward. This implies that the log-level data are capturing the primary variation in defects, but some board-level relationships are likely being lost. Further work will explore the nested relationships between boards and logs as well as the nonlinearities in variable relationships.

CANCOR was used to determine if possible predictive relationships exist between defect variables (DECAY, INDEC, GRUB, SHOT, PIN, STAIN, MINER, OTHER, TOTAL) and nondestructive log measurements, including the acoustic velocity and DBH (C_L, DBH). Tables 6 and 7 give the results for the CANCOR based on correlation matrices from the log-level and the log-board data after standardization, respectively. From Table 6, the hypotheses tests indicate that the first canonical correlation is significantly different from zero, whereas the second is not. The first canonical correlation vector for the defect-variable group shows that it weights positively on defect count, followed by DECAY, OTHER, and INDEC, and negatively on PIN. The first canonical correlation vector for the nondestructive group negatively weights on acoustic speed and DBH. Together (Fig 5), a larger value for the weighted combination of the first set of variables (ie from increased defect counts, decay, other defects and/or incipient decay, and lower pin worm value) is positively correlated with a larger value for the negatively weighted combination of the second set of variables (ie from a lower acoustic speed and DBH).

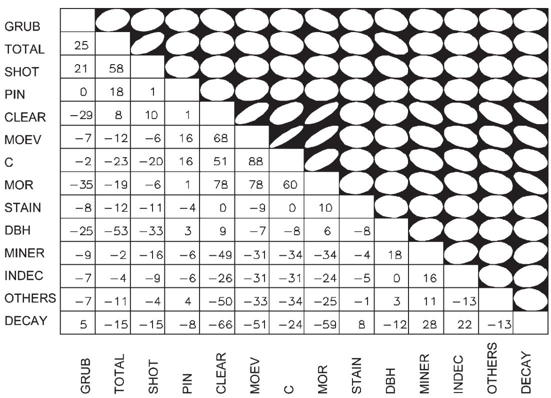

Figure 3. Corrgram representation of the correlation matrix for the defect, nondestructive, and strength variables.

To further understand the relationship of the canonical variables to the original variables, Fig 6 repeats Fig 5 with a minigraph for each

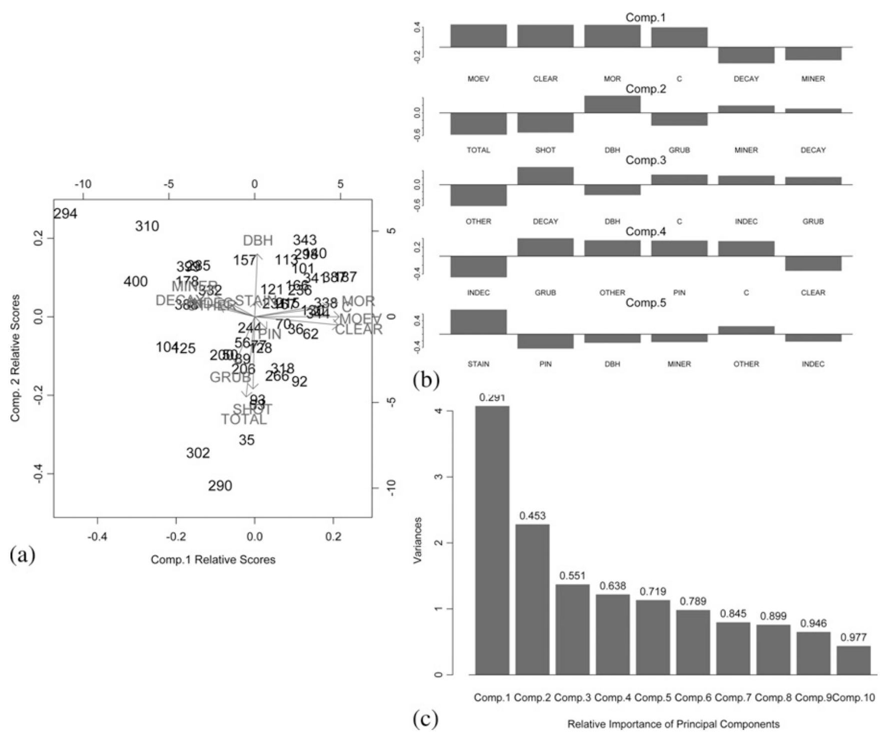

Figure 4. (a–c) Principal component analysis of log-level data.

Table 6. *Results of the canonical correlation analysis based on the correlation matrix formed from the standardized log-level data.*

Variable group	Variable	Coefficients for canonical variables Dimension 1	Dimension 2
Defects	Total	0.113	0.079
	Decay	0.064	0.017
	Grub	0.008	0.021
	InDec	0.043	−0.051
	STAIN	0.021	0.017
	Miner	−0.003	−0.093
	Shot	0.021	−0.034
	Pin	−0.043	0.003
	Other	0.074	−0.054
Nondestructive measures	DBH	−0.101	−0.108
	C_L	−0.116	0.092
Singular value		0.72	0.26
Canonical correlation		0.85	0.51
Tests of significance (*p* value)		<0.0001	0.1521

DBH, diameter at breast height.

Table 7. *Results of the canonical correlation analysis based on the correlation matrix formed from the standardized log-board data.*

Variable group	Variable	Coefficients for canonical variables Dimension 1	Dimension 2
Defects	Total	0.067	−0.033
	Decay	0.052	−0.003
	Grub	0.026	−0.030
	InDec	0.029	0.029
	STAIN	0.010	−0.010
	Miner	0.002	0.055
	Shot	0.010	0.004
	Pin	−0.016	−0.009
	Other	0.039	0.039
Nondestructive measures	DBH	−0.061	0.062
	C_L	−0.067	−0.056
Singular value		0.48	0.15
Canonical correlation		0.69	0.39

DBH, diameter at breast height.

defect variable and the percentage of clear wood. In each minigraph, each log is marked with an intensity indicator representing the relative original defect value (darker indicates a higher value with the exception of percent clear wood where darker indicates a lower value).

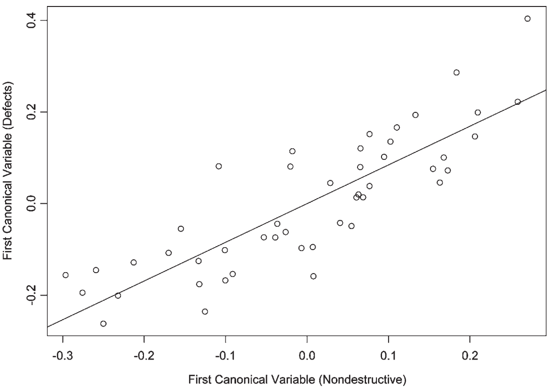

Figure 5. CANCOR plot of the canonical correlation variables of the standardized log-level data.

The CANCOR analysis on the standardized log-board data is summarized in Table 7. Although the overall correlations are reduced, there still appear to be substantial relationships. The canonical coefficients for the defect group shift weights to some of the lesser-occurring defects, indicating that exploring preprocessing alternatives to the mean may lead to even higher correlations. It should also be kept in mind that with the log-board data, logs with a greater number of boards, essentially are given more weight in this analysis. Figure 7 repeats Fig 6 but each board is plotted.

CONCLUSIONS

Four hundred small-diameter red oak logs harvested from four Ozark timber stands exhibiting oak decline as evidenced by elevated levels of red oak borer activity were nondestructively evaluated using a resonance-based acoustic technique. Logs were subsequently processed into boards for determining the extent of borer infestation and evaluating the potential grade yield and mechanical properties of the logs. Although acoustic measurement appears capable of discerning the wood quality of borer-infested red oak logs on a stand basis, the within-stand acoustic variation points to the technique's

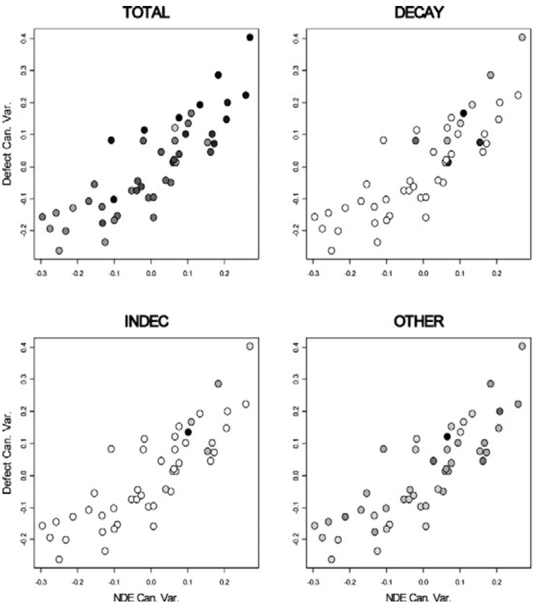

Figure 6. CANCOR plot of the canonical correlation variables of the standardized log-level data with each log marked with an intensity indicator representing the log's value for the particular label (darker indicates a higher value with the exception of percent clear wood where darker indicates a lower value).

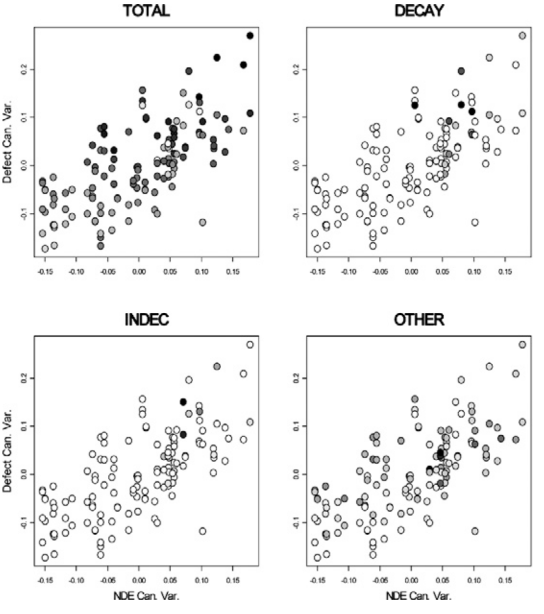

Figure 7. CANCOR plot of the canonical correlation variables of the standardized log-board data with each log marked with an intensity indicator representing the log's value for the particular label (darker indicates a higher value with the exception of percent clear wood where darker indicates a lower value).

major advantage of segregating logs within the stand.

The inspection and defect mapping of the Missouri red oak boards revealed a wide range of severe defects, many of them unsound. The difference between the defect distributions for the Missouri boards and the boards in the 1998 data bank indicates that grub holes, shot worm holes, pin worm holes, decay, incipient decay, and mineral streak are those defects most likely associated with the borer infestation.

Yield results showed that, overall, only 23% of the boards were graded as No. 2 and better (which qualifies them for high-value products), and the majority of the boards were in extremely low grades (No. 3 and Pallet stock), which reflects the quality problem associated with oak decline in the region. The yield of high-quality boards showed good positive relationships with the log acoustic velocity, whereas the yield of low-quality boards decreased significantly as the log acoustic velocity increased.

Principal component analysis based on the correlation matrix showed positive relationships among acoustic values, mechanical properties, and relative amount of clear wood. Canonical correlation analysis showed relationships between a linear combination of log acoustic velocity and DBH and a linear combination of log defect measurements.

The results of this study indicate that the acoustic-based technique has good potential to be used to segregate stems and logs harvested from borer-infested timber stands. Future research is planned to apply similar acoustic techniques to standing trees in stands exhibiting varying levels of borer activity and determine if it is effective in assessing wood quality before the trees are harvested.

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