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**Effect of the degree of decay on the electrical resistance
of wood degraded by brown-rot fungi**

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Abstract

There have been limited efforts to investigate the association between wood decay and electrical resistance. Therefore, we examined the change in the electrical resistance of wood progressively decayed by brown-rot fungi to elucidate the effect of the degree of decay. The rate of mass loss of wood was used as an indicator of the degree of fungal decay. The changes in the moisture content and ion concentrations were measured at various decay stages. The results showed a significant difference in the electrical resistances of sound wood and fungal-treated wood after 24 weeks. The electrical resistance significantly decreased with the exposure time. The degree of decay increased as the mass loss increased, resulting in the severe breakdown of cell walls and the accumulation of fungal mycelia. Empirical models related to the rate of mass loss and the percent decrease in the electrical resistance were established. The moisture content and cation concentrations increased to various degrees in decayed wood. The increase in the cation concentration was considered to play a dominant role in the decrease in the electrical resistance. The study results provide valuable information for developing an electrical-resistance-based method coupled with ion content measurements for incipient wood decay detection.

Keywords: electrical resistance; ion concentration; mass loss; moisture content; degree of wood decay.

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Introduction

Nondestructive testing (NDT) methods for wood decay detection and wood quality evaluation have been increasingly developed in recent years. The widely used tools are generally based on ultrasound waves, stress waves, microdrilling, and electrical-resistance methods (Brazee et al. 2011; Gao et al. 2017). The electrical resistance of wood was previously used as an indicator to determine the fiber saturation point of wood (Stamm 1929). The electrical resistance as a function of the moisture content (MC) can provide information regarding the water content of wood and is therefore used along with other techniques to estimate the transverse MC distribution in trees (Brischke and Lampen 2014). Electrical-resistance-based nondestructive methods are found to be effective for both MC estimation and wood decay detection (Goraevan and Anoviakstephen 2015). Studies focused on the electrical-resistance properties of progressively deteriorating standing trees began in the 1970s (Tattar and Shigo 1972). These studies have elucidated the potential of resistance measurements for wood decay detection. The Shigometer, which is based on electrical-resistance measurements, was developed to detect wood decay (Shigo and Shigo 1974). Thereafter, there have been considerable efforts to understand the association between wood decay and the electrical properties (Shortle and Smith 1987, 1988). In recent years, a few NDT methods based on electrical-resistance measurements, including impedance tomography and spectroscopy, have been widely used to map the resistivity, through which the decay area in a tree can be located (Oliva

et al. 2015).

When attacked by bacteria after prolonged exposure beneath soil and water, wood naturally undergoes physical degradation such as mass loss (ML), decreases in mechanical properties, and biological decay by white-, brown-, or soft-rot fungi (Smith and Shortle 1988). The rot-causing fungi that feed on wood are multicelled fibrous organisms; their hyphae spread over the wood and secrete enzymes. The enzymes dissolve woody cells and thus cause decay of wood (Jones and Worrall 1995). Consequently, the changes in the mechanical properties of wood when subjected to biological decay severely affect the characteristics of wood, such as electrical conduction, MC, acoustic propagation, elasticity, and plasticity (Bari et al. 2016). The electrical resistance of wood decayed by fungi presents an obvious decreasing trend, and the concentrations of metals associated with the increase in the conductivity of decayed wood have been discussed (Shortle and Shigo 1973; Shortle 1982).

Most recently, Kirker et al. (2016, 2017) measured the electrical resistance of wood decayed by brown-rot fungi and examined how fungi affect the resistance by individually analyzing the effects of moisture, ion translocation, and fungal decay on the resistance. They concluded that the changes in the resistance caused by decay (ML) were significantly smaller than those caused by moisture. The increase in the concentration of ions has been considered one of the reasons for the decrease in the electrical resistance of decaying wood. It is well-known that wood-decaying fungi can increase the moisture level of wood; however, it is not clear whether MC or ion content plays a more important role in lowering the electrical resistance of wood. There have been limited efforts to thoroughly investigate the comprehensive effects of the ML, MC, and key ion

concentrations on the electrical resistance of wood decayed by fungi.

The aims of this study were to (1) systemically investigate the changes in the electrical resistance, MC, ion concentrations, rate of ML, and microstructure in decaying wood and (2) quantify the relationships between these parameters to elucidate the effect of the degree of decay on the electrical resistance of wood.

Materials and Methods

Sample preparation

Wood disks were cut at a breast height of 1.3 ± 0.13 m from 46-year-old larch (*Larix olgensis*) and poplar (*Populus ussuriensis*) trees located in Great Young Forest Stand in the Grand Khingan Mountain ($52^{\circ}20'N$, $124^{\circ}42'E$, 412 m a.s.l.), northeast of China. The sapwood of the larch and poplar disks was used to obtain 42 small samples (with dimensions of 20 mm radial $\times$ 20 mm tangential $\times$ 50 mm longitudinal planes), which were then numbered. The fresh samples were air-dried to an MC of $23\% \pm 2\%$ to avoid any microcracks and oven-dried at $103 \pm 3^{\circ}C$ to a constant weight. The oven-dried samples were then soaked in distilled water for fungal exposure. The weights of the oven-dried and soaked samples at various moisture levels were measured to determine the initial MC of sound wood (MC_{sw}) before fungal exposure. At each decay treatment stage, the wet weight of an exposed sample was measured to determine the MC of the decaying sample (MC_{dw}) before the electrical-resistance test.

Fungal cultures and exposure

The fungal species used in this study is the brown-rot fungi *Gloeophyllum trabeum* (Pers.

117 *exFr.*) *Murrill*. It is one of the wood preservative strains specified by the American
118 Society for Testing and Materials (Forest Products Laboratory 1999). The strain was
119 procured from the China General Microbiology Culture Collection Center. The fungal
120 culture and exposure were carried out according to the specifications in Chinese Standard
121 GB/T 13942.1-2009 (Chinese Standard 2009). The feeder strips used were polar wood
122 that was clear of knots, damage, or defects with dimensions of 5 mm × 20 mm × 20 mm.
123 The fungal strain was grown in a 500-mL flask to establish an active mycelium. The
124 sapwood blocks were sterilized by autoclaving at 121 °C for 60 min. Twenty-one flakes
125 (42 samples) were set up for each wood species. Two sapwood blocks were placed in
126 each flask. Eighteen flasks inoculated with fungus were used as the treatment group, and
127 three flasks not treated with fungus were used as the control. After the complete growth
128 of fungal mycelia, the wood blocks were exposed to the mycelia in flasks from weeks 4
129 to 24 at 23 ± 2°C and a relative humidity (RH) of 65% ± 5%. The decaying wood blocks
130 were evaluated at 4-week intervals up to 24 weeks (a total of six exposure stages, four
131 weeks per stage).

132 ***Electrical-resistance measurement***

133 At the end of each exposure stage, the electrical resistance of wood was measured. The
134 wood samples were removed from the culture flasks, and the adhered mycelia were
135 carefully scraped using a stiff brush. The digital bridge method was used to measure the
136 electrical resistance of wood (Gao et al. 2018). At each exposure stage, after measuring
137 the wet weight of an exposed sample, 2-mm-diameter copper electrodes were inserted
138 into both ends of the block up to a depth of about 5 mm and connected to the test circuit
139 (Fig. 1a). A schematic of the digital bridge (TL2812D) used to measure the electrical

140 resistance of wood is shown in Fig. 1b.. The testing voltage was 5 V with automatic
141 ranging and an alternating current (AC) signal with a frequency of 1000 Hz. The electrical
142 resistance (R) was recorded after the reading was stable for 30–60 s. After a resistance
143 measurement, the wood sample was weighed to observe the ML to determine the mass of
144 wood at various decay stages. During the measurements, the change in the MC of a
145 sample was observed (no more than 3%). The wood blocks were oven-dried at $103 \pm 3^\circ\text{C}$
146 for 23 h after a resistance measurement and weighed again to calculate the rate of ML.
147 Generally, the loss of strength is used as an indicator of incipient decay instead of the
148 weight loss or ML. However, common standard decay tests (e.g., standards EN 113 and
149 ASTM D2017) use the weight loss as a measure of decay (Curling et al. 2002). We
150 selected the rate of ML as the indicator of wood decay. At the final exposure stage (24
151 weeks), the same experimental procedures were carried out for the blocks of the control
152 group. The rate of ML, E_{ML} (%), was calculated using the following equation:
153
$$E_{\text{ML}} (\%) = 100 \times (WD_b - WD_a) / WD_b \quad (\text{Eq. 1})$$

154 where WD_b (g) is the initial dry weight before exposure and WD_a (g) is the final dry weight
155 after exposure (Bari et al. 2016).

Microscopic examination

A scanning electron microscope (SEM; Quanta-200, FEI Inc., Beaverton, OR) was used for the observation of wood block surfaces decayed by fungi at various exposure stages. The treated and control blocks were compared. Two-millimeter-thick laths were cut with razor blades from the edges of sapwood blocks parallel to the longitudinal wood surface. The laths were trimmed using a sliding microtome, carefully mounted on an SEM stub with a conductive adhesive, and coated with Au to a thickness of about 12 nm by a sputter coater. The acceleration voltage, spot size, and working distance were 15 kV, 2–3 mm, and 10 mm, respectively. SEM images at magnifications of 500 $\times$ and 1000 $\times$ were obtained. Breakdown of the middle lamella and the primary and secondary transverse sections was not obviously observed in early exposure stage.

Inductively coupled plasma optical emission spectrometry analysis

An elemental analysis of the cations was conducted by energy dispersive X-ray analysis (EDAX; FEI Inc. Beaverton, OR). It has been reported that ions play an important role in the fungal decay process of lignocellulose biomaterials and—more broadly—fungal metabolism. K, being a highly mobile cation in solution, has been shown to have a strong effect on the electrical resistance of wood (Tattar et al. 1972). Shortle (1982) examined the relationships among the changes in the electrical resistance, MC, and concentrations of soluble positive ions during the developmental stages of the white rot and brown rot of Douglas-fir sapwood and heartwood, and the total concentrations of K, Ca, and Mg were measured. Kirker et al. (2017) reported that fungi contributed to the active transport

of some ions such as Fe, Mn, and Ca. Therefore, the energy spectra and relative concentrations of five key cations—K, Ca, Mg, Fe, and Mn—in sound and decaying wood were examined in this study. Inductively coupled plasma optical emission spectrometry (ICP-OES; PerkinElmer Optima 8000, PE Co., Waltham, MA) was used to determine the concentrations of cations in inoculated wood at various exposure stages. The mycelia adhering to the exposed wood blocks were removed using a clean razor. The exposed blocks at different stages of decay were oven-dried for 23 h at 104 °C after determining their fresh weights. The dry weights of the wood blocks were measured in silica crucibles, and the rate of ML was calculated. The oven-dried blocks were then ashed in a muffle furnace at 550 °C for 6 h and passed through a 100-mesh sieve to prepare the sample for cation analysis. The ash (0.5 g) obtained from wood at different stages of decomposition was placed in a single cooled crucible, wetted with deionized distilled water, and digested with 2 mL of 50% HClO₄ and 5 mL of concentrated HNO₃ overnight. The solution was heated for 2 h at 100 °C and boiled for 8 h at 200 °C in a DigiBlock EHD36 digester (LabTech, Beijing, China). After cooling, 25 mL of the sample solution was placed in a volumetric flask. The concentrations of five key cations were measured by ICP-OES. An overview of the experimental process is presented in Fig. 2.

Statistical methods

A one-way analysis of variance (ANOVA) of the measured electrical resistances of 36 fungal-treated samples of poplar and larch at six exposure stages (six samples per stage) was performed. An ANOVA is used to determine whether the differences between the means of six groups of data are statistically significant to ascertain the effect of the fungal exposure time on the degree of decay of the wood. Because a one-way ANOVA cannot

specifically determine which groups are different, a post-hoc least significant difference (LSD) test was carried out to perform multiple comparisons between the decay intervals to better understand how decay influences the resistance over the exposure period.

Results

Characterization of the degree of decay

The degree of decay of wood was characterized using the rate of ML and microscopic structural changes; it was graded in terms of the rate of ML. The degree of decay of wood treated with brown-rot fungi became severe as the exposure time increased. The control and treated wood samples of poplar and larch were observed using an SEM to analyze the structural breakdown caused by fungi. Figures 3 and 4 present a clear view of the anatomical characteristics of the observed samples. The catheter lumen of the control poplar was clean. The pit was neat, and its membrane was intact before the decay treatment (Fig. 3a). Figures 3b–3f show the tangential and radial views of the microscopic structural changes and the corresponding MLs at various exposure stages. The observations revealed the presence of fungal mycelia in the parenchyma cells of poplar wood, and the structure of the parenchyma cell walls started to disintegrate four weeks after exposure to fungi (Fig. 3b). The rate of ML was approximately 12% during the early 4-week exposure period, and there was an increase in the growth of mycelia in the vessels. The pits in the vessels appeared enlarged and obviously deformed and were even perforated eight weeks after exposure when the rate of ML was approximately 23% (Fig. 3c). The degradation of wood became more severe as the exposure time increased, and there was a corresponding increase in the ML. At an exposure time of 24 weeks, the hyphae swelled and clustered, the pit edge appeared cracked, and fungal mycelia

significantly accumulated and twined the agglomerate mutually (Fig. 3f). The degradation of wood was extremely severe 24 weeks after fungal treatment. The cells almost ruptured, the mycelial ball filled the wood-cell lumen, and the rate of ML was approximately 65% (Fig. 3f).

The overall trend in the microscopic structural changes in larch was similar to that of poplar throughout the exposure period. The microscope images revealed similar decay patterns for both species (Figs. 4a–4f). The decay rate of larch wood was slower than that of poplar by 63.0%–87.5% throughout the entire exposure period. The rate of ML of larch was relatively lower than that of poplar, especially during the early stages of exposure.

Brown-rot fungi remove both lignocellulose and structural carbohydrate by selectively degrading cellulose and hemicellulose, resulting in a significant loss of wood mass. Therefore, a higher rate of ML is observed when the destruction of microscopic structures by fungi is more severe. The rate of ML was used as an indicator of the degree of decay of fungus-degraded wood, and the degree of decay was divided into different ranks (Table 1). According to the overall trend in the rate of ML during the exposure period, a rank for popular wood denotes a range of 10% of E_{ML} and is prefixed by “D” (e.g., D1 means that $E_{ML} = 0\%–10\%$, D2 means that $E_{ML} = 10\%–20\%$, etc.). For larch wood, a range of 5% of E_{ML} was used (Table 1).

Electrical-resistance characteristics in relation to the degree of decay

The average electrical resistances of the sound wood samples, treated samples (exposed to fungi), and control samples (untreated wood) are shown in Fig. 5. A significant difference in the electrical resistances of the sound and treated samples was observed.

The average electrical resistance of treated wood was considerably lower than that of sound wood 24 weeks after incubation. The decreases in the electrical resistances of poplar and larch wood were approximately 98% and 81%, respectively. The electrical resistance of untreated larch wood was lower than that of sound wood and higher than that of fungal-treated wood.

A one-way ANOVA of the electrical resistances of 36 fungal-treated samples at six exposure stages (six samples per stage) was performed at a 95% level of confidence. The difference in the electrical resistances was significant among different stages. As the F values of poplar (39.01) and larch wood (2733.89) were significantly higher than that of $F_{\alpha = 0.05}$ (2.53 for poplar and 2.54 for larch), both P values were less than 0.01. This indicated that the electrical resistance of wood dependent on the fungal exposure time is significantly related to the degree of decay of the wood. The results of the LSD of the post-hoc tests for larch showed that the mean difference between six decay intervals was significant at the 0.05 level. For poplar, multiple comparisons of the LSD showed that the mean difference between the 4-week and other decay intervals was significant at the 0.05 level, except those between the 8- and 12-week intervals and between the 20- and 24-week intervals.

Table 2 summarizes the electrical resistances of fungal-treated wood at various exposure stages. R_b (k Ω) and R_a (k Ω) represent the average measured electrical resistances of wood before and after fungal treatment, respectively. The percent decrease in the electrical resistance at each exposure stage is represented using E_{Rd} (%), which was calculated using the following equation:

$$E_{Rd} = 100 \times |R_b - R_a|/R_b \quad (\text{Eq. 2})$$

270 The electrical resistance of wood significantly decreased 24 weeks after exposure.
 271 The average percent decrease in the electrical resistance (E_{Rd}) over the exposure period
 272 ranged from 77.1% to 81.4% for poplar and from 81.7% to 97.8% for larch. The increases
 273 in the rate of ML at various decay stages are listed in Table 2. E_{ML} (%) was calculated
 274 using Eq. 1 and increased with the exposure time from weeks 4 to 24. The average E_{ML}
 275 ranged from 10.6% to 66.6% for poplar and from 2.5% to 20.3% for larch. Figure 6 shows
 276 the trends in the percent change in the electrical resistance and in the rate of ML (E_{ML})
 277 with the exposure time. The percent decrease in the resistance (E_{Rd}) for decaying poplar
 278 wood marginally increased with the exposure time. A similar trend in E_{Rd} was observed
 279 for decaying larch wood. E_{ML} of poplar significantly increased with the exposure time,
 280 with a rapid increase after 12 weeks. E_{ML} of larch wood exhibited a similar trend, but the
 281 rate of increase was relatively slower than that of poplar.

282 The electrical resistance versus the rate of ML of progressively decayed wood is
 283 shown in Fig. 7. The overall trends in the electrical resistance were similar for both
 284 species throughout the exposure period. The percent decrease in the electrical resistance
 285 (E_{Rd}) was highly sensitive to the rate of ML when E_{ML} increased from 0% to 30% for
 286 poplar (Fig. 7a) and from 0% to 15% for larch (Fig. 7b). E_{Rd} significantly increased
 287 initially with E_{ML} for both wood samples; then, the rate at which E_{Rd} increased decreased
 288 when $E_{ML} > 30\%$ for poplar (Fig. 6) and $>15\%$ for larch (Fig. 7b). On the basis of this
 289 observation, empirical models were built to fit the trends in the electrical resistance versus
 290 the rate of ML of poplar and larch. Logarithmic relationships were established between
 291 E_{Rd} and E_{ML} ; $E_{Rd} = 4.07\ln E_{ML} + 64.63$ with a coefficient of determination (R^2) of 0.68 for
 292 poplar, and $E_{Rd} = 7.78\ln E_{ML} + 74.52$ with $R^2 = 0.69$ for larch.

Changes in the moisture content and ion concentration

Table 3 presents the changes in the MCs of the samples before and after fungal exposure from weeks 4 to 24. The average MCs of samples at six decay stages ranged from 87.8% to 238.5% for poplar and from 54.7% to 120.4% for larch. The MCs of treated samples were greater than 50%, which is above the fiber saturation point of wood, and the increase in the MC ranged from -8.4% to 243.9% for poplar and from 38.1% to 263.3% for larch.

The trends in the average cation concentration throughout the exposure period are shown in Fig. 8. The concentrations of Fe in both larch and poplar wood tended to increase with the exposure time, with a rapid increase after 12 weeks. Twenty weeks after the exposure of larch wood, the concentration of Fe suddenly decreased and increased at 24 weeks. However, the overall concentration of Fe in both species exhibited an increasing trend during the decaying process. The concentrations of K and Ca in larch wood constantly increased before week 16 and then decreased at week 20. At week 24 of exposure, the concentration of K in larch wood remained constant, whereas the concentration of Ca marginally increased. In both larch and poplar wood, the concentration of Mn exhibited an increasing trend throughout the exposure period. The trends in the ion concentrations marginally varied among cations. The concentrations of five markers (cations) determined by ICP-OES are presented in Table 4. The change in the concentration of each cation with exposure time was in agreement with the EDAX results, except for a marginal variation in the concentrations of the cations measured by the two methods. The results obtained by ICP-OES revealed that the concentration of Ca in both species was higher than those of the other cations and significantly increased with the exposure time. In larch wood, the concentrations of K, Mg, and Fe steadily increased

with the exposure time, but the change in the concentration of Mn was not obvious. In poplar wood, The concentrations of K, Mg, Fe, and Mn insignificantly changed with the exposure time (Table 4). The percent increase in the total concentration of cations of decayed wood relative to that of untreated wood at each exposure stage is shown in Fig. 9. The percent increase in the total concentration of five cations increased with the exposure time.

Discussion

The decrease in the resistance of untreated wood compared with that of sound wood was probably due to the increase in the concentration of metal ions in wood. The increases in the cation concentrations in decaying wood were consistent with the findings of other studies (Shortle 1982; Ostrofsky et al. 1997). Moreover, it has also been demonstrated that ions can be translocated from soil to wood, and fungi play an important role in this process (Kirker et al. 2017). Kirker et al. (2017) reported that fungi contributed to the active transport of some ions such as Fe, Mn, and Ca from the soil in an inoculated flask into wood, and an increased concentration of metals is often associated with an increased decay-related ML. The logarithmic decrease in the electrical resistance with the increase in the rate of ML observed in the present study indicates that the ML apparently decreases the electrical resistance of decaying wood. The ML of wood is due to the destruction caused by decay fungus. We speculate that the ions move from soil to wood and permeate more easily when the cell walls of wood are damaged by the fungus; therefore, the number of charge carriers increases, which consequently decreases the electrical resistance. However, the trend in the electrical resistance versus the ML is contrary to the findings of Kirker et al. (2016). They found that the electrical resistance of wood significantly

decreased with the increase in the ML until approximately 10% ML. In the present study, the resistance of wood did not evidently change; instead, it remained constant when the ML was greater than 10%. The reason for this discrepancy is still unclear. It might be due to the difference in the sample species used or the difference in the sampling position. Therefore, further studies are necessary to improve the results and accurately quantify the effect of the ML on the resistance of wood decayed by fungi.

The resistance of treated wood was significantly lower than that of sound wood. Generally, the decrease in the resistance could be attributed to the increase in the MC in decayed wood because the resistance of wood decreases as the MC increases, and a logarithmic relationship exists between them (Gao et al. 2018). Our results revealed that the MC significantly increases after a fungal attack, which is generally greater than 50% when wood starts to decay after the fungal attack. Because the resistance was not sensitive to the change in the MC and became constant when the MC was greater than 30% in sound wood (Kirker et al. 2016; Gao et al. 2018), the decrease in resistance cannot be attributed to the increase in the MC of decayed wood. Furthermore, as the electrical resistance exhibited a decreasing trend throughout the decay period from 4 to 24 weeks, the decrease in the resistance cannot simply be attributed to the increase in the MC of decaying wood but may significantly depend on the changes in the cation concentrations.

Because the ions of minerals carry an electric current, the number and mobility of ions affect the rate of current flow and the electrical resistance according to Kohlrausch's Law (Lin 1967). Accordingly, it is suggested that an increase in the relative cation concentration in decayed wood results in a decrease in the electrical resistance. Kirker et al. (2017) found that fungi actively control the distribution and amount of ions during the

decay process, which supports the results of the present study well. However, the reason for the decreases in the concentrations of Fe and Mn at 20 weeks (Fig. 8) is still not clear, especially the precipitous decrease for Fe in larch at 20 weeks; we cannot simply attribute this phenomenon to the sampling error. We speculate that it results from redox reactions of Fe with inorganic substances, acid–base reactions, and deoxyribonucleic acid (DNA) synthesis and cleavage in general metabolic processes at the time of mass reproduction of decayed bacteria. Fe is a component of the extracellular enzymes responsible for lignin degradation in fungi and is a cofactor of many enzymes involved with oxidation/reduction reactions (Jellison et al. 1997). More work is needed to verify these results.

In the present study, we found that the decreasing resistance of decaying wood is related to both the ML and the changes in the ion concentrations. This finding is consistent with that of Kirker et al. (2017). However, the effect of the change in the MC on the resistance is minimal compared to that of the ion concentration. The decrease in the electrical resistance during the decay of wood was accompanied with a rapid increase in the ion concentration of wood.

Therefore, the results of this study are expected to act as a reference to develop an electrical-resistance-based method coupled with ion content measurements for evaluating the degree of decay of wood, especially for the detection of incipient decay. This will help with harvest scheduling and the application of treatments during forest assessment.

Conclusions

We systemically examined the changes in the electrical resistance, ML, MC, and ion concentrations in larch and poplar wood progressively decayed by brown-rot fungi. The degree of decay of wood was characterized using the rate of ML and microscopic

structural changes, and the effect of the degree of decay on the electrical resistance of wood was elucidated. The following conclusions can be drawn on the basis of the results of the present study:

(1) The degradation of wood became more severe as the exposure time increased, and there was a corresponding increase in the ML. The electrical resistance of decaying wood significantly decreased as the exposure time increased. There was significant accumulation of fungal mycelia, severe destruction of cell walls, and an increase in the rate of ML with the exposure time; moreover, severe degradation occurred 24 weeks after exposure.

(2) The rate of ML and its relationship with the electrical resistance were quantified. Logarithmic empirical models were established between the percent decrease in the electrical resistance (E_{Rd}) and the rate of ML (E_{ML}): $E_{Rd} = 4.07\ln E_{ML} + 64.63$ ($R^2 = 0.68$) for poplar and $E_{Rd} = 47.78\ln E_{ML} + 74.52$ ($R^2 = 0.69$) for larch.

(3) The MC of fungus-treated wood significantly increased to various degrees for decayed wood, with a maximum of 263.3%. The percent increase in the total concentration of five cations increased with the exposure time.

(4) The decrease in the resistance of decayed wood cannot simply be attributed to the increase in the MC of decaying wood but may significantly depend on the changes in the cation concentrations. The effect of the change in the MC on the resistance was insignificant compared to that for the ion concentrations.

The findings of this study are expected to act as a reference to develop electrical-resistance-based NDT instruments for wood decay detection in the field to assist with harvest scheduling and treatment application.

408

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Tables

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Fig. 2. Overview of the experimental process.

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Fig. 4. A scanning electron microscope (SEM) images of radial and tangential views of untreated and fungal-treated larch (*Larix olgensis*) wood at various stages of exposure to the brown-rot fungi *Gloeophyllum trabeum*. (a) a tangential view of untreated larch wood

(500×); (b) a tangential view of treated wood with a mass loss of 2.8% four weeks after exposure (1000×); (c) a tangential view of treated wood with a mass loss of 4.4% eight weeks after exposure (1000×); (d) a tangential view of treated wood with a mass loss of 8.1% 16 weeks after exposure (500×); (e) a tangential view of treated wood with a mass loss of 13.0% 20 weeks after exposure (500×); (f) a radial view of treated wood with a mass loss of 31.6% 24 weeks after exposure (500×).

Fig. 5. Average electrical resistance variation in different poplar (*Populus ussuriensis*) and larch (*Larix olgensis*) wood types.

Fig. 6. Percent decrease in electrical resistance and mass loss rate of poplar (*Populus ussuriensis*) and larch (*Larix olgensis*) wood with decay treatment time.

Fig. 7. Relationship between the percent decrease in electrical resistance change and mass loss rate of poplar (*Populus ussuriensis*) and larch (*Larix olgensis*) wood.

Fig. 8. Changing trends in the average concentration of potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), and manganese (Mn) with exposure time obtained by the EDAX method.

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Table 1 Empirical classification of the degree of decay by the rate of mass loss.

Exposure time (weeks)	Poplar		Larch	
	$*E_{ML}$ (%)	Degree of decay	E_{ML} (%)	Degree of decay
4	10.6 ± 3.4	<i>D2</i>	2.5 ± 1.4	<i>D1</i>
8	22.4 ± 3.6	<i>D3</i>	2.8 ± 0.8	<i>D1</i>
12	28.4 ± 6.6	<i>D3</i>	3.9 ± 1.7	<i>D1</i>
16	47.3 ± 3.0	<i>D5</i>	8.5 ± 1.9	<i>D2</i>
20	54.8 ± 5.8	<i>D6</i>	20.3 ± 10.2	<i>D4</i>
24	66.6 ± 3.8	<i>D7</i>	18.9 ± 4.6	<i>D4</i>

$*E_{ML}$ represents the percent increase in the mass loss calculated using $E_{ML} = 100 \times (WD_b - WD_a)/WD_b$, where WD_b and WD_a represent the average dry weights before and after fungal exposure, respectively. A rank for popular wood denotes a range of 10% of E_{ML} and is prefixed by “D” (e.g., *D1* means that $E_{ML} = 0\%–10\%$, *D2* means that $E_{ML} = 10\%–20\%$, etc.). For larch wood, a range of 5% of EML was used. Note: Since the average $E_{ML}(\%)$ of larch at 20 weeks is 20.3 with an SD of 10.2, it is more appropriate to classify the degree of decay of larch in this period to *D4*.

Table 2 Average measured electrical resistance and percent change at various stages of exposure.

Exposure time (weeks)	Poplar			Larch		
	R_b (k Ω)	R_a (k Ω)	E_{Rd}^* (%)	R_b (k Ω)	R_a (k Ω)	E_{Rd}^* (%)
4	45.8	12.8	72.1 ± 3.9	268.4	49.1	81.7 ± 10.4
8	46.6	11.3	75.8 ± 4.7	170.3	23.8	86.0 ± 6.2
12	53.3	11.9	77.7 ± 0.7	236.5	20.9	91.2 ± 4.8
16	52.3	10.8	79.3 ± 1.0	236.8	12.4	94.8 ± 4.8
20	51.1	9.9	80.6 ± 2.1	218.2	30.3	86.1 ± 5.3
24	50.6	9.4	81.4 ± 1.7	229.3	5.1	97.8 ± 1.5

* E_{Rd} represents the percent decrease in the electrical resistance and was calculated using $E_{Rd} = 100 \times (R_b - R_a)/R_b$, where R_b and R_a represent the average electrical resistances of wood before and after fungal exposure, respectively.

Table 3 Change in the moisture contents of samples with the exposure time.

Species	Exposure time (weeks)	MC _{sw} (%)	MC _{dw} (%)	Percent increase in the MC (%)
Poplar	4	118.8 ± 21.5	108.6 ± 24.4	(-8.4) ± 16.4
	8	90.9 ± 17.9	136.1 ± 33.4	49.7 ± 24.2
	12	30.0 ± 10.8	87.8 ± 14.4	237.9 ± 164.4
	16	113.9 ± 23	186.9 ± 9.7	68.8 ± 29.9
	20	94.9 ± 24.7	238.5 ± 60.9	161.1 ± 72.1
	24	93.0 ± 68.3	211.7 ± 129.2	125.2 ± 101.5
Larch	4	41.0 ± 9.7	54.7 ± 7.0	38.1 ± 26.1
	8	35.5 ± 15.0	71.0 ± 18.7	112.4 ± 47.7
	12	18.5 ± 3.4	65.9 ± 15.1	263.3 ± 88.0
	16	44.8 ± 18.7	86.5 ± 7.3	109.8 ± 50.7
	20	43.3 ± 11	114.6 ± 31.8	177.7 ± 107.3
	24	42.1 ± 10.0	120.4 ± 20.9	192.9 ± 47.5

MC_{sw} is the moisture content of the sound wood sample before decay treatment.

MC_{dw} is the moisture content of the decayed wood sample after fungal exposure.

Table 4. Average content of each marker cation measured by ICP-OES.

Species	Exposure time (weeks)	Fe (mg/g)	Mn (mg/g)	K (mg/g)	Ca (mg/g)	Mg (mg/g)
Poplar	0	0.049 ± 0.013	0.012 ± 0.002	0.070 ± 0.021	0.645 ± 0.090	0.075 ± 0.010
	4	0.032 ± 0.010	0.014 ± 0.012	0.165 ± 0.033	0.853 ± 0.110	0.109 ± 0.049
	8	0.040 ± 0.014	0.014 ± 0.098	0.168 ± 0.034	1.006 ± 0.130	0.095 ± 0.002
	12	0.157 ± 0.053	0.016 ± 0.038	0.180 ± 0.042	1.006 ± 0.090	0.143 ± 0.053
	16	0.128 ± 0.077	0.037 ± 0.022	0.117 ± 0.036	1.478 ± 0.046	0.195 ± 0.076
	20	0.133 ± 0.086	0.027 ± 0.032	0.207 ± 0.056	1.580 ± 0.087	0.101 ± 0.068
	24	0.201 ± 0.092	0.036 ± 0.045	0.316 ± 0.072	1.664 ± 0.099	0.142 ± 0.068
Larch	0	0.058 ± 0.010	0.002 ± 0.001	0.061 ± 0.001	0.216 ± 0.060	0.039 ± 0.008
	4	0.055 ± 0.020	0.003 ± 0.004	0.113 ± 0.075	0.508 ± 0.091	0.109 ± 0.039
	8	0.088 ± 0.034	0.004 ± 0.001	0.242 ± 0.049	0.556 ± 0.067	0.110 ± 0.046
	12	0.154 ± 0.078	0.007 ± 0.001	0.328 ± 0.056	0.693 ± 0.071	0.178 ± 0.089
	16	0.249 ± 0.086	0.006 ± 0.005	0.379 ± 0.078	0.944 ± 0.088	0.154 ± 0.069
	20	0.283 ± 0.084	0.016 ± 0.009	0.428 ± 0.066	1.016 ± 0.095	0.193 ± 0.082
	24	0.442 ± 0.096	0.033 ± 0.009	0.566 ± 0.081	1.421 ± 0.101	0.210 ± 0.053

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