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Development of wood decay in wound-initiated discolored wood of eastern red cedar

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Abstract

Logs of eastern red cedar, *Juniperus virginiana* L., with well-developed bands of light-colored wood (''included sapwood'') within heartwood can be unsuitable for sawn wood products. This finding is in contrast to published information that the ''included sapwood'' is (1) a heartwood anomaly rather than sapwood and (2) its occurrence is not a reason to exclude this type of wood from commercial use. The alternative view presented here is that ''included sapwood'' is wound-initiated discolored wood which is the starting point for wood decay in living trees and which has adversely altered wood properties before the development of decay symptoms. Our study of the patterns of discoloration and decay, electrical resistance properties, elemental analysis, wood acidity, solubility in dilute NaOH, total phenol content, and tests of wood decay resistance indicated that the so-called included sapwood was discolored wood. This light-colored discolored wood had no greater decay resistance than sapwood, a common finding in other tree species in which ''included sapwood'' is found. Half the sample disks sent to our laboratory had symptomatic decay within the bands of light-colored discolored wood bounded by a phenol-enriched protective layer on the bark side and phenol-enriched heartwood on the pith side of the band. This ring-rot, even in its pre-symptomatic stage, can cause problems during processing for sawn wood products. Therefore, logs with well-developed bands of light-colored discolored wood should be considered high-risk material for some products, although they could be useful for others.

Keywords: decay resistance; discolored wood; ''included sapwood''; wood properties.

Introduction

An Environmental Scientist of the Kentucky Division of Forestry reported in February 2007 that a sawmill operator was experiencing increased cull in eastern red cedar owing to white streaking, a problem which has long existed but appeared to be worsening. Preliminary examination indicated the problem was ''included sapwood'' seen as patches or bands of white wood within the reddish heartwood. The white streaking showed up for varying lengths at one position or reappeared at several positions in the log. Some of the white areas were considered ''dotty'', indicating early stages of wood decay. Such wood did not maintain its structural integrity and tended to flake when sawn making it unsuitable for sawn products, although the cull logs could be used for shavings of lower value.

These observations appeared to contradict published research on red cedar which concluded that ''included sapwood'' should be considered anomalous heartwood rather than sapwood and that ''this anomaly should no longer be a reason to exclude this type of wood from commercial utilization'' (Bauch et al. 2004). An alternative view is that ''included sapwood'' is wound-initiated discolored wood based on its association with wounds (McGinnes et al. 1969) and on the color patterns interpreted through models of the development of discoloration, decay, and compartmentalization of decay derived from the dissection of thousands of trees (Shigo and Marx 1977). Discolored wood is neither sapwood nor heartwood. Discolored wood forms from sapwood exposed to a wide variety of wounds and undergoes a three-stage process ending in wood decay (Shigo and Hillis 1973). This process of progressive infection and decomposition takes place within boundaries described by the compartmentalization concept and the CODIT model (Liese and Dujesiefken 1996; Shortle 2000). If both sapwood and heartwood are present at time of wounding, decay begins in discolored sapwood and spreads into discolored heartwood (Shortle 1979). Wood decay in its early previsual stage can adversely alter wood properties making it unfit for some products.

The objectives of this study were to determine how bands of discolored wood in eastern red cedar differ from sapwood and heartwood and how the presence of discolored wood can adversely affect wood utilization. Parameters used to classify red cedar stemwood into progressive stages of decay include symptomology, electrical resistance of extract, pH, solubility in dilute NaOH, total phenol content, and decay resistance.

Materials and methods

Sample materials were provided by the Kentucky Division of Forestry and consisted of eight disks taken from freshly cut logs after a commercial harvest of eastern red cedar (*Juniperus virginiana* L.). The color patterns on the transverse surface of the disks were equivalent to those observed at sawmills where problems in wood quality have occurred. The disks were air dried by placing the disks on

edge with both transverse surfaces open to the air in a dry room. The air-dry disks were then shipped to Durham, NH, USA. These disks were 2.5–4 cm thick and 9–21 cm diameter inside bark. All disks had complete or partial bands, generally 1–2 cm wide, of light-colored wood within the dark purplish-red heartwood. Each disk was photographed on both faces before and after sanding (Figure 1). Wood samples for chemical analysis were drilled from zones of sapwood, heartwood, discolored wood, and decayed wood.

The initial diagnostic examination of the disks indicated two symptomatic cases of brown-rot (Figure 1E4, G3) and two symptomatic cases of white-rot (Figure 1D2 and H2, a white pocket rot) within the bands of wound-initiated discolored wood, commonly called ''included sapwood'' in red cedar. Dark layers at the outer limit of the light-colored discolored wood were considered to be the column boundary layer compartmentalizing the infection following wounding. The boundary layers were dated to 12–14 years prior to harvest and to 32 years for the inner band with brown-rot (Figure 1E). This indicated that the outer bands had been exposed to the three-stage decomposition process for 1–1.5 decades and the inner band for 3–3.5 decades. Therefore, the bands of discolored wood and the contiguous heartwood could exist as the non-infected first stage or the infected, previsual second stage existing prior to the observed symptomatic infected third stage.

To test for progressive degradation of discolored wood and heartwood using sound sapwood as a point of reference, 2–4 holes (depending on the size of the disk) were drilled from designated positions (Figure 1) with a 6.5 mm brad-pointed titanium-coated bit with the shavings caught on paper and transferred to polyethylene vials for storage. The drilling yielded 500–1000 mg of air-dried wood shavings for diagnostic tests. Air-dried weights of wood shavings used for each diagnostic test were converted to oven-dried weights using a moisture correction factor determined by oven drying 50 mg subsamples overnight at 103°C to determine the oven-dry weight. For each subsample, the oven-dry weight was divided by the air-dry weight. The mean of the subsample determinations was a moisture correction factor of 0.96.

Wood ionization determined as extract electrical resistance (ER): 29–31 mg of air-dried wood shavings were placed in disposable 10 ml beakers. Three 1.0-ml portions of deionized water were squirted into the beaker by pipet to mix the water and wood. After 1 h incubation at room temperature (RT), electrical resistance was measured by a double-pin electrode with 1.6 cm pin spacing (Delm-

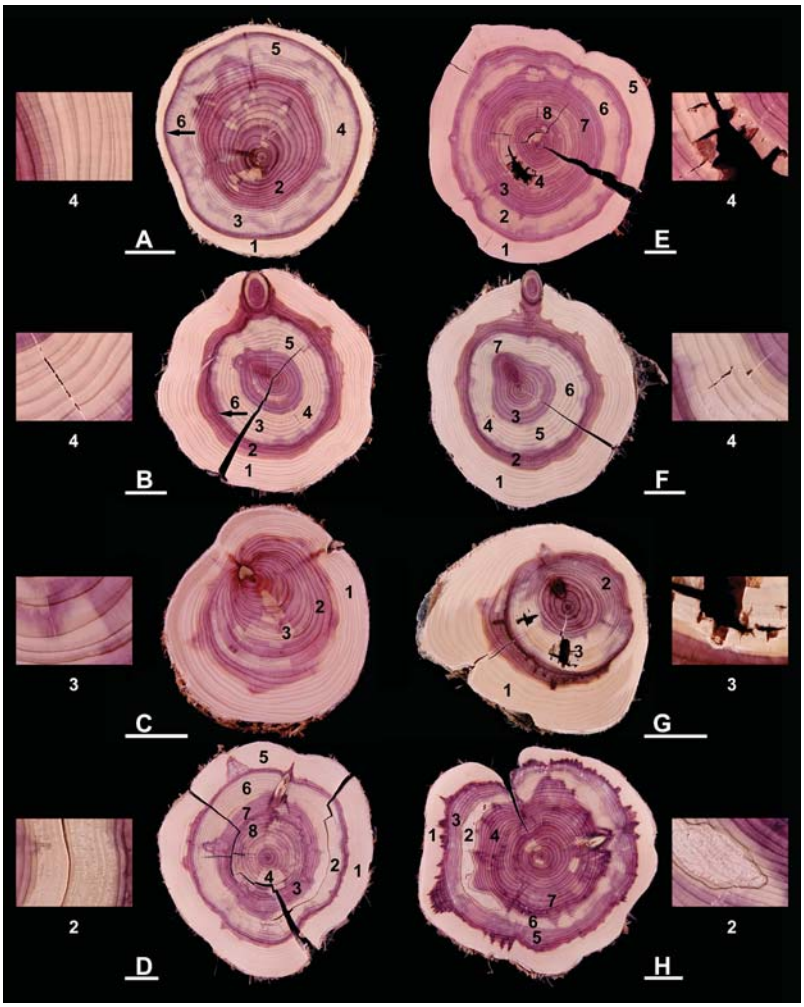

Figure 1 Transverse view of sample disks from eight eastern red cedar trees (A–H); numbers indicate sampling positions; arrows in disk A and B indicate the position of the protective column boundary layer. A magnified view of one sampling position is given for each disk. Scale bars are 3 cm.

horst Instrument Company, Towaco, NJ, USA) attached to a model OZ 87 Shigometer (Osmose Wood Preserving Company, Buffalo, NY, USA). The electrode pins were placed vertically into the slurry of water and wood and readings were recorded as kilo-Ohms (kΩ) of resistance.

Wood acidity (pH) determination: 32–36 mg of air-dried wood shavings were weighed into 10×75 mm test tubes with 0.32–0.36 ml of 5 mM $CaCl_2$ solution added to yield 1 mg per 0.01 ml. After 1 h incubation at RT, pH measurements were made by a refillable combination pH electrode with a long, thin 7×245 mm epoxy body (Beckman Instruments, Inc., Fullerton, CA, USA) attached to a microcomputer-based portable pH meter (Jenco Instruments, Inc., San Diego, CA, USA). The electrode was inserted into the base of the small tube while turning the tube left and right to be sure the slurry covered the tip of the electrode and was evenly distributed around it's bulb. Reading of pH was recorded to 0.01 unit.

Determination of total phenol content: 31–35 mg of air-dried wood shavings were weighed into 10×75 ml test tubes with 1.0 ml of 76% ethanol added. During 1 h of extraction in a heater block at 70°C, tubes were briefly vortexed after 20 min. The extracts were cooled to RT and 0.2 ml of extract solution was transferred by pipet into a 13×100 mm test tube and 2.1 ml of deionized water was added. After vortexing the extract and water, 0.6 ml of phenol reagent (prepared by 1:2 dilution of Folin-Ciocalteu phenol reagent, 2 N) was added and mixed by vortexing. After exactly 3 min, 1.0 ml of 1.0 M Na_2CO_3 was added and mixed by vortexing. The final solution was then incubated for 1 h at RT and the absorbance was measured at 650 nm in a spectrophotometer (Spectronic 20D+, Thermo Spectronic, Rochester, NY, USA). The total phenol content was estimated based on the absorbance of a standard gallic acid curve and expressed as mg g^{-1} gallic acid.

Solubility in dilute NaOH: 101–110 mg of air-dried wood shavings were placed in 50 ml disposable polypropylene beakers with 5.0 ml of 0.2 M NaOH added. Beakers were covered with aluminum foil and autoclaved for 15 min at 121°C. Once cooled to RT, the residue was filtered on tared fritted glass crucibles (porosity C) and rinsed with three 10 ml portions of deionized water, two 10 ml portions of 0.1 M HNO_3, and again with three 10 ml portions of water. The crucibles were then placed in a 103°C forced hot-air oven and dried overnight. The final oven-dried weight of wood residue was determined by subtracting the crucible weight from the oven-dried crucible plus residue. The initial oven-dried weight of sample was calculated by multiplying the air-dried weight by the moisture correction factor, 0.96. The loss on extraction (LOE) was calculated by the following equation: LOE, % = [(initial OD wt − final OD wt)/initial OD wt] × 100.

Essential elements – P, K, Ca, and Mg – were extracted by freeze-thawing in 10 mM HCl according to the method of Minocha and Shortle (1993) using 30 mg wood samples in 6 ml of 10 mM HCl. Element concentration in extracts was determined by inductively coupled plasma – atomic emission spectroscopy (ICP-AES: Varian Vista CCD, Palo Alto, CA, USA).

Decay resistance relative to sapwood was determined based on a new two-stage micro-decay test. Radial wood strips 1 cm wide were cut through sapwood (SW) into heartwood (HW) and bands of discolored wood (DW) in red cedar disks. Small blocks – approximately 2 mm thick and of uniform tissue type – were then split from the wood strip to yield three collections (SW, HW, DW) of blocks approximately 2×10×30 mm in size. A collection of SW and HW blocks were prepared from red spruce which has non-durable heartwood compared to red cedar. The blocks were placed in 13×100 ml disposable borosilicate glass test tubes and oven-dried for 2 h in a forced hot-air oven at 103°C. Blocks were cooled and the oven-dry weight recorded. Blocks were placed back in the tubes, covered with aluminum foil, and sterilized by autoclaving 15 min at 121°C. The cooled, sterilized blocks were placed next to actively growing cultures of *Postia placenta*, a brown-rot fungus, or *Trametes versicolor*, a white-rot fungus, on malt-yeast agar with the tangential face down. After the wood blocks were covered with mycelium (35 days) and the wood became hydrated and ionized, the blocks were transferred aseptically to moist tube chambers for aeration to accelerate decay. The moist chambers were made using 17×100 mm polypropylene round-bottomed tubes into which strips of Whatman 3MM chromatography paper (2×7 cm) curved around a laboratory marker pen were inserted and wetted with 0.75 ml of deionized water. The tubes were covered with polypropylene caps and sterilized by autoclaving 15 min at 121°C. When the infected, hydrated, and ionized wood blocks were placed into the chamber the edges touched the sides of the tube covered with the moist paper leaving the upper and lower surfaces of the block open to aeration and slow drying.

The decaying wood blocks were removed after 35 days of incubation on agar followed by 40 days incubation in the moist chamber at 25°C. Mycelium was carefully removed from the surface. Blocks were placed in aluminum pans, oven-dried overnight at 103°C, cooled in desiccators, and weighed. Weight loss as a result of decay was calculated as follows: weight loss, % = [(initial OD wt − final OD wt)/initial OD wt] × 100.

For each set of wood samples in each test the mean and 95% confidence intervals (CIs) of replicate samples were determined. Significant differences were indicated using the overlap rules for 95% CI bars (Cumming et al. 2007).

Results

Wood was classified based on visual inspection (Figure 1) and determination of electrical resistance of extract, ER, (Figure 2, Table 1). Healthy sapwood (SW) occurred at 10 positions (Figure 1A1, B1, C1, D1, 5, E1, 5, F1, G1, H1) and was used as points of reference for comparing heartwood (HW) and discolored wood, ''included sapwood'' (DW), both of which originated as SW. Sound HW occurred at 11 positions (Figure 1A2, B2, C2, D3, 7, 8, F2, 3, H4, 5, 7), was reddish purple in color, and had ER greater than that of SW (Figure 2). Sound DW occurred at 14 positions (Figure 1A3–6, B3–6, C3, D4, F5–7, H6), was light colored in bands 1–2 cm wide, and had ER greater than that of sapwood (Figure 2).

Both sound HW and sound DW had a mean ER significantly greater than SW and a significantly lower pH (higher acidity) than SW (Figure 2A, B). The pH of HW was significantly less than DW. Solubility in dilute NaOH and total phenol content of DW did not differ significantly from SW, whereas that of HW was significantly greater than SW or DW (Figure 2C, D). The potassium and phosphorus concentration of HW and DW were significantly less than SW (Figure 3A, B). Ca concentration of DW was less than that of SW, but greater than in HW; and Mg concentration of DW overlapped in SW and in HW which were significantly different (Figure 3C, D).

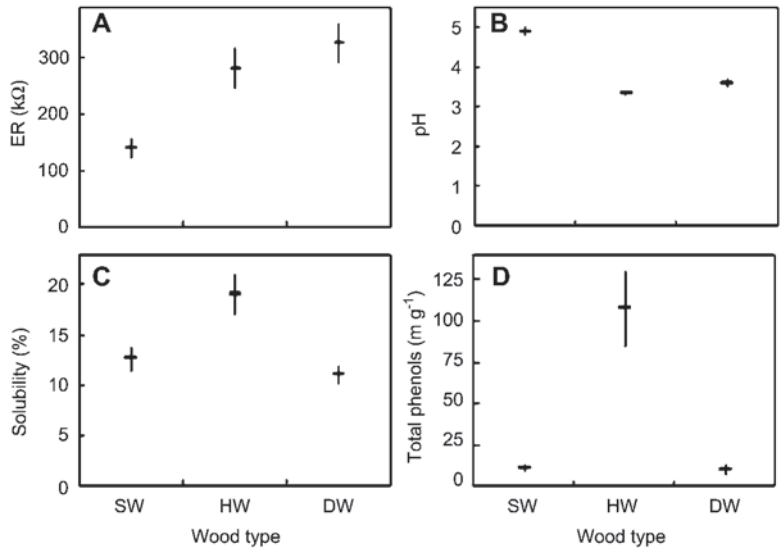

Figure 2 Mean and 95% confidence interval of extract electrical resistance (ER), pH, dilute NaOH solubility, and total phenols; wood type: SW = sapwood, HW = sound heartwood, and DW = sound discolored wood.

Infected DW and HW in stages 2 and 3 of the three-stage wood decay process occurred at 13 positions, varied in appearance, and had ER less than that of SW (Table 1). Nine positions were characteristic of brown-rot infections (Figure 1E2–4, 6–8, F4, G2–3) having a significantly lower ER (34 ± 9 kΩ) and pH (2.7 ± 0.1) than sound SW, HW, or DW (Figure 2). Two positions with symptomatic brown-rot infection (stage 3) occurred within a DW band (Figure 1E2, G3) and had a content soluble in dilute NaOH $>30\%$ (Table 1) which is indicative of cellulose depolymerization. One position with previsual brown-rot infection (stage 2) within a DW band (Figure 1F4) had a dilute alkali solubility of 30%. Three positions with previsual brown-rot infections in DW (Figure 1E 2,6,8) and in HW (Figure 1E3,7, G2) contiguous with symptomatic brown-rot had a dilute NaOH solubility (stage 2 DW, $14 \pm 3\%$; stage 2 HW $18 \pm 4\%$) equivalent to sound DW and HW (Figure 2). Four positions were characteristic of white-rot infections. Two positions with symptomatic white-rot infection (Figure 1D2, H2) occurred within a DW band and had a lower ER than sound SW, HW, or DW, but similar pH and solubility in dilute NaOH compared to sound wood. Two positions with previsual white-rot infection in DW (Figure 1D6) and HW (Figure 1H3) had slightly to moderately lower ER than sound SW and equivalent pH and solubility to sound DW and HW. The patterns of infected wood indicate that brown-rot and white-rot infections begin in DW and spread into contiguous DW and HW.

Table 1 Range of electrical resistance (ER), pH, and dilute alkali solubility (DAS) of infected discolored wood (DW) and heartwood (HW) indicated by an electrical resistance less than SW (position, see Figure 1).

Decay type	Wood type	Position	ER (kΩ)	pH	DAS (%)
Brown-rot					
Symptomatic	DW	E4; G3	16–18	2.6–2.7	55–74
Previsual	DW	E2,6,8; F4	29–47	2.7–3.0	11–30
	HW	E3,7; G2	37–42	2.7	17–20
White-rot					
Symptomatic	DW	D2; H2	48–61	3.3	13–17
Previsual	DW	D6	89	3.5	13
	HW	H3	126	3.4	15

After incubation in decay tests, red spruce SW and HW were covered with a dense fluffy mycelial mat of *Postia placenta* and a dense leathery appressed mat of *Trametes versicolor.* Red cedar SW and DW had the same type of mycelial mat development, but HW had very sparse mycelial development by both fungi. Weight loss caused by the brown-rot fungus *P. placenta* was greater than 50% in red spruce SW and the loss in its non-durable HW was equivalent to the loss in SW (Figure 4). Under the same conditions, weight loss in red cedar DW was greater than 25% and equivalent to SW, whereas weight loss in HW was less than 2% (Figure 4). Weight loss caused by the white-rot fungus *T. versicolor* was greater than 25% in red spruce SW and the weight loss of its non-durable HW was equivalent to the weight loss in SW (Figure 4). Under the same conditions, weight loss in red cedar DW was approximately 10% and equivalent to SW, whereas weight loss in HW was less than 2%.

The dark-colored narrow band of wood occurring at the outer edge of the discolored wood (Figure 1A, B) was taken to be the column boundary layer (reaction zone or barrier zone) of the wound-initiated discolored wood. This layer had a total phenol content equal to or greater than in HW and much greater than in the SW without and the DW within (Figure 5). This dark layer observed in all but one disk was 12–14 rings inside the bark indicating a wound age and external exposure of little more than a decade during which infection could spread in the wound-initiated discolored wood. A second dark band was observed in the disk with

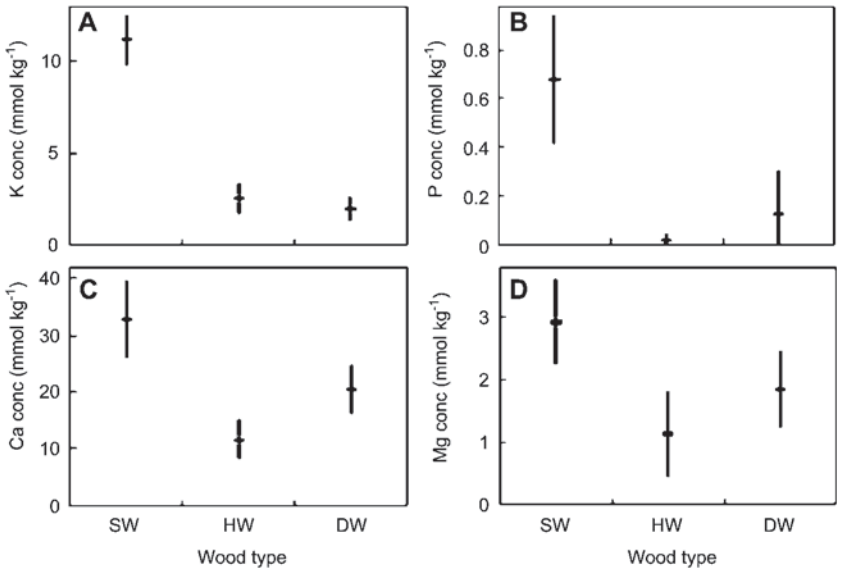

Figure 3 Mean and 95% confidence interval of K, P, Ca, and Mg concentrations; wood type: SW = sapwood, HW = sound heartwood, and DW = sound discolored wood.

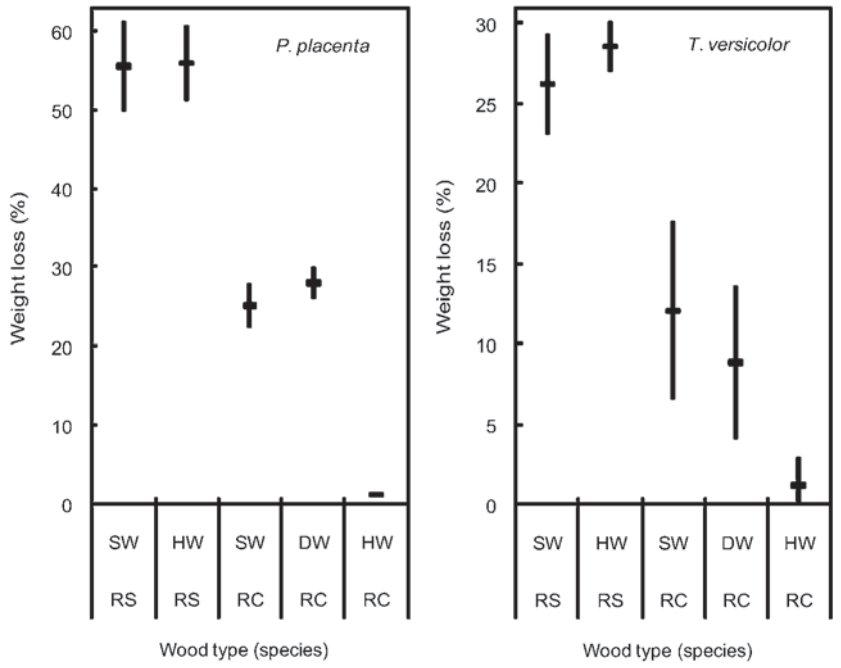

Figure 4 Mean and 95% confidence intervals of weight loss owing to decay caused by a brown-rot fungus, *P. placenta*, and a white-rot fungus, *T. versicolor*, in SW = sapwood and HW = sound heartwood of red spruce = RS, a species with slightly or no decay resistant heartwood; and SW = sapwood, HW = sound heartwood, and DW = sound discolored wood of red cedar = RC, a species with highly decay resistant heartwood.

brown-rot in the inner discolored wood band that dates to approximately 32 years (Figure 1E). Development of decay in bands of DW initiated by wounding and bounded by phenol-rich protective zones (bark side) and durable HW (pith side) therefore appears to take 1–3 decades, whereas decay of HW had not occurred after more than 3 decades of exposure.

Discussion

The symptomology of decay in the bands of discolored wood initiated by wounding was consistent with the most common types of decay reported in eastern red cedar (Hepting 1971; Lawson 1990). Cubical brown rot is caused by *Fomes subroseus* and *Daedalea juniperina*, a white pocket rot is caused

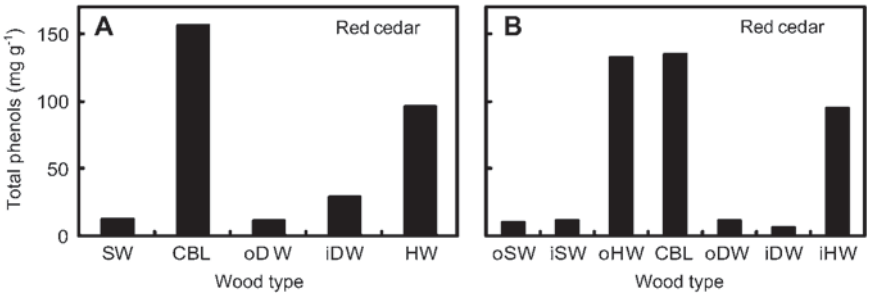

Figure 5 Variation in total phenols in sapwood = SW, the column boundary layer = CBL at the outer bounds of sound discolored wood = DW [subdivided into an outer (oDW) and inner (iDW) portions], and sound heartwood = iHW interior to DW in red cedar disk A (see Figure 1); in disk B (see Figure 1) the same zones were sampled, but SW was subdivided into outer sapwood = oSW and inner sapwood = iSW, and outer sound heartwood = oHW was added.

by *Pyrofomes demidoffii*, and a white rot and butt rot by *Heterobasidion annosum*. The first three fungi appear to enter through dead branch stubs and the corky conks of the brown-rot fungus *D. juniperina* can be found under many dead branch stubs on larger trees. This habit is common in *Trametes pini*, a white pocket rot fungus causing a ring rot in white pine (Shigo and Marx 1977, pp. 44–45). The development of decay in wood exposed by branch stubs or other types of wounds proceeds through the discoloration and decay process taking place in bands between a phenol-enriched column boundary layer on the bark side and phenol-enriched, decay resistant HW on the pith side (Figures 1 and 5). This pattern in transverse view appears as presented in the CODIT model for HW-forming tree species with multiple wounds and multiple column boundary layers (Shigo and Marx 1977, p. 39). In eastern red cedar, the same type of banding pattern occurs for a single wound. Unlike the triangular pattern of discoloration for the non-durable HW tree species investigated to illustrate the process (Shigo and Marx 1977, p. 29), in durable HW species like red cedar the discoloration is truncated to form a band bounded internally by the durable HW which acts like the column boundary layer.

The initial stage of DW development or HW formation involves deionization as indicated by increased ER (Shigo and Shortle 1985; Shortle 1990). In both cases, mobile K ions are resorbed along with P into the living sapwood (Meerts 2002). The resorption of Ca and Mg was less from DW than HW. Deionization in red cedar involved a marked increase in acidity, measured as a decrease in pH. The infection of DW and HW by a brown-rot or white-rot fungus involves ionization as indicated by decreased ER (Table 1, Figure 2). Ionization, which is a rapid process taking only a few days in decay tests (Shortle 1990), can extend for distances up to several meters along the grain (Shortle and Hill 1987). The decreased ER is due to increased K, and to a lesser extent Mg and Ca, although mobile H ions in brown-rot could contribute more than mobile K ions (Shortle 1982). In brown-rot, the wood rapidly becomes acidic and eventually more soluble in dilute NaOH, as indicated by low pH and a high NaOH solubility (Table 1) (Cowling 1961; Shortle 1990). In white-rot, there is no initial change in wood acidity and no marked increase of solubility in dilute NaOH.

There was a marked difference in total phenol content between red cedar HW and DW, which had a phenol content equivalent to SW (Figure 2). The high phenol content was caused by flavanols (Bauch et al. 2004) which are known to inhibit decay (Scheffer and Cowling 1966), although they are poor growth inhibitors of wood-decay fungi. Sesquiterpenes found in high concentration in red cedar HW are inhibitory to the growth of wood-decay fungi, but did not appear to contribute to decay resistance in DW, which reportedly had three times the concentration of sesquiterpenes in SW, but less than 1/10 the concentration of sesquiterpenes in HW (Bauch et al. 2004). A combination of high concentrations of flavanols that inhibit wood decay and of high concentrations of sesquiterpenes that inhibit growth of wood-decay fungi probably accounts for the exceptional decay resistance of red cedar HW.

Decay tests with the brown-rot fungus *P. placenta* caused weight loss of more than 50% in both SW and non-durable HW of red spruce and 25–30% in red cedar SW and DW while causing less than 2% weight loss in durable cedar HW, which is known for its very high decay resistance. The exceptional decay resistance of red cedar SW compared to SW of other tree species has been previously reported (Platt et al. 1965). The low dose of sesquiterpenes observed in SW and DW (Bauch et al. 2004) could be sufficiently fungistatic to retard the growth of decay fungi to account for the lower weight loss per unit time (Figure 4) compared to spruce wood lacking sesquiterpenes. Decay tests with the white-rot fungus *T. versicolor* caused weight loss of approximately 25% in red spruce SW and HW. This lower rate of decay by *T. versicolor* (more commonly a decayer of hardwood tree species) was observed in earlier experiments with many decay fungi (Ostrofsky et al. 1997). As in the case of *P. placenta*, the weight loss caused by *T. versicolor* on cedar SW and DW was approximately half that of spruce, whereas weight loss on cedar HW was less than 2%.

The low decay resistance of wound-initiated DW (called by the quoted authors as ''included SW'') has been observed in oak (Dujesiefken et al. 1984), eucalyptus (Wilkes 1985, 1986), Douglas-fir (Kennedy and Wilson 1956), and western red cedar (MacLean and Gardner 1956). The lack of wood-preserving phenolic substances in wound-initiated DW is a

common feature and is probably as a result of the loss of phloem contact following wounding as protective column boundary layers form to compartmentalize infections entering the exposed sapwood. Blockage of rays observed in wounded red cedar prevents the movement of carbohydrates essential for biosynthesis of flavanoids (Bauch et al. 2004). The importance of phloem contact through rays for the formation of phenol-enriched protective layers has been reported for red maple (Shortle et al. 1995).

Changes in wood properties occur long before visible symptoms of advanced decay are perceptible, which become evident at approximately 15–20% weight loss. Toughness (impact bending strength) is reduced by 50% or more before 3% weight loss from either white-rot or brown-rot (Kirk and Cowling 1984) is reached. Other types of strength loss occur during brown rot owing to a rapid reduction in the degree of polymerization of cellulose as indicated by increased solubility in dilute NaOH (Cowling 1961).

Conclusions

One view of ''included SW'' in eastern red cedar is that a wound causes anomalous HW to form. Because that wood is a type of HW, not SW, its presence should not be a reason to exclude this type of wood from commercial use (Bauch et al. 2004). This is a view of wound-altered wood that assumes a static condition observed shortly after its formation.

An alternative view based on this case study is that ''included SW'' is wound-initiated discolored wood (DW) which forms from SW exposed by wounding. Wound-initiated DW undergoes dynamic biological processes of degradation and decomposition within the limits of protective layers of wood as trees survive and grow during the decades following wounding. Our sample of wood from freshly cut red cedar logs contained the various stages from sound, non-infected wood to wood in advanced stages of decay. Therefore, red cedar logs with well-developed bands of wound-initiated DW should be considered a high risk material that is being altered by early stages of decay and that has no greater durability than red cedar SW; thus, limiting their commercial value. There is a need to discover the primary causes of wounding in red cedar and to manage red cedar to reduce wounds that initiate discoloration and infection. There is also a need to eliminate terms such as ''included SW'' based on color differences and to focus on the biological processes taking place in trees that progressively alter wood properties.

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