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Histochemical and Geometric Alterations of Sapwood in Coastal Douglas-Fir Following Mechanical Damage during Commercial Thinning

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Histochemical and geometric alterations to sapwood in mechanically damaged Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco) trees were quantified 14 years after thinning. Discoloration and decay were measured in felled damaged and undamaged trees. Compartmentalized walls were identified and measured macroscopically. Sapwood to heartwood ratio was measured incrementally along the boles.

Results showed a distinct reaction zone forming at the time of injury. Compartmentalized walls 1–3 were less distinct and heavily resinous streaking was evident in extant tissues, particularly in the axial direction. Post-damaged sapwood was burl-like for 4–6 years and tracheids contained resin-filled lumina. Damaged wood volumes were modeled by multiple regression. Wound depth, wound area, and diameter inside bark (DIB) accounted for 73% of the discolored volume ($p = 0.02$). DIB alone accounted for just over 55% of the response. Post-damaged sapwood averaged 15 mm (SE = 2.3 mm) greater in width on the side opposite the damage along the length of the boards. Wound area explained just over 65% of this response ($p = 0.003$). Sapwood area was not significantly different between damaged and control trees ($p = 0.56$). Results indicate that wounded Douglas-fir trees may slow conversion of sapwood to heartwood on the bole side opposite the wound, possibly as a response to maintain sapwood area necessary for physiological maintenance of the existing crown. About 19% of the lower bole volume in damaged trees was affected by discoloration and secondarily by structural changes. Reduction in value of the lower log can be as high as 19% by conventional bucking practices. Alternatives are presented to reduce the value loss to between 2.5% to 3.5%.

Keywords compartmentalization, damages, *Pseudotsuga menziesii*, sapwood, thinning
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1 Introduction

Commercial thinning has accelerated as a result of public pressures to reduce safety risks such as harvest-related landslides (Fredriksen 1970, Swanson and Dyrness 1975), reduce visual impacts from clear-cut operations (Berris and Bekker 1989, McDonald and Litton 1998), and increase multiple-use opportunities in forests (Shindler and Cramer 1999). Additionally, global demand for forest products is expected to continue to rise significantly and an increasing proportion of this is expected to be commercially thinned. U.S. consumption alone is expected by 2050 to rise by as much as 28% over early 2000 consumption (Haynes et al. 2007). Private timberland owners in western Oregon and Washington are projected through 2044 to harvest an increasing portion of timber volume by commercial thinning and other intermediate treatments following pre-commercial-thinning (Adams and Latta 2007). Forest policies in British Columbia, Canada mandated a proportion of the Provincial annual cut to commercial thinning and anticipated commercial thinning yields were expected to account for 10–15% of the B.C. annual harvest volume by 2007 (B.C. Ministry of Forests and Range 1997).

A number of studies report a high incidence of residual stem wounding during mechanized thinning operations (Aulerich et al. 1974, Benson and Gonsior 1981). The location of damage on the bole of the tree is important because the primary value is located in the butt log and generally decreases with successively higher logs (Bettinger and Kellogg 1993). Studies of Douglas-fir (Hunt and Krueger 1962), western hemlock, and Sitka spruce (Wright and Issac 1956, Shea 1960, Wallis and Morrison 1975) have shown that large wide scars low on the bole of the tree are more prone to fungal infection than injuries in other locations.

Earlier studies on wound response led to the development of two major models that described histological post-wounding response; 1) compartmentalization of decay in trees (CODIT) (Shigo and Marx 1977, Shigo 1984) and 2) a related model of reaction zone creation (Shain 1967, 1971, 1979).

Compartmentalization of decayed and discolored tissues has been described extensively (Shigo 1965, Shigo and Marx 1977). Compartmentalization is a series of chemical and anatomical processes formed as either active (Shigo 1984) or passive (Boddy and Rayner 1983) boundaries in response to invasion of wood tissue by microorganisms. Four "walls" have been described (Shain 1979, Shigo 1984) including: wall 1 – resisting vertical spread of pathogens; wall 2 – resisting inward radial spread; wall 3 – resisting lateral spread; and wall 4 (called a reaction zone) – resisting spread to newly formed tissues.

Criticism of the CODIT model has focused primarily on lack of attention to the role of moisture/air content in the wood (Schmidt 2006). In addition, the model does not discriminate between active responses in living sapwood tissue and passive responses in heartwood tissue (Schwarze et al. 1999). Neither criticism negates the presence of compartmentalization but instead both question primary active host response to microorganisms.

Concerns over interpretations of the CODIT model led to the formation of an alternative model (Boddy and Rayner 1983) based on response to embolisms in ruptured and adjacent xylem tissues to contain losses in stem conductivity, in turn causing a breach of internal environment via changes in wood moisture content and oxygen tension (Yamada 2001). The model proposed that fungal defenses proposed by CODIT were only secondary effects of wound response.

The opacity of the materials and the long time frames involved make it difficult to determine if stem responses to wounding are primarily designed to protect conductivity or prevent pathological invasion. Regardless of the purpose, it is clear that wounding and subsequent changes in wood conductivity and chemistry have the potential to affect the quality of the wood in this most valuable part of the bole. While this is largely accepted, there are few data on how wounds affect sapwood area in important commercial species including Douglas-fir.

The purpose of this study was 1) to quantify changes in sapwood cross-sectional area in managed Douglas-fir following mechanical damage of the boles during commercial thinning operations, 2) to examine results of this study with regard to existing models of wound response, 3) to examine differences in post-thinning sapwood radial dis-

Table 1. Characteristics of the sites selected for study.

Site	Age	Quadratic mean diameter, cm (s.e.)	Quadratic mean diameter range, cm	Total height, m (s.e.)	Live crown height, m (s.e.)	T/ha (s.e.)	BA/ha m^2 (s.e.)	Stand density index
1	50–60	46.6 (1.8)	21.8–66.3	35.7 (0.8)	14.5 (0.7)	289.5 (33.1)	49.5 (3.1)	310.5
2.	50–60	43.6 (1.2)	22.9–38.4	31.6 ((0.5)	12.9 (0.5)	332.5 (24.3)	49.8 (2.3)	319.9

Table 2. Characteristics of wound measurements from the damaged sample trees (n = 18). All wounds were caused by ground-based logging equipment during commercial thinning activities.

	Lngth, cm	Width, cm	Area, cm^2	Depth, cm	Length to width ratio	Height above ground, m
Mean	71.5	38.1	2716.9	3.3	2.1	2.0
Std error	6.7	3.2	383.8	0.8	0.3	0.2
Range	39.6–137.2	18.3–64.0	1040.5–7943.2	0.3–12.7	0.8–6.2	0.9–3.8

tance, and 4) to develop a model for prediction of affected wood volume for use by land managers for quantifying the effects of thinning damage.

2 Methods

2.1 The Study Sites

The study sites were located at the McDonald-Dunn Forest managed by the Oregon State University College of Forestry. The sites were 3 km west of Corvallis, Oregon (44°33’N, 123°15’W) and were on 5 to 35% northeast-facing slopes. Annual precipitation over the last 20 years was 1100–1500 mm and mean annual air temperature was 12°C. The soil is a clayey, mixed mesic, Dystric Xerochrept. The site is classified as a *Tsuga heterophylla/Acer circinatum/Gaultheria shallon* community type (Hubbard 1991). The second-growth stands are dominated by 50- to 60-year-old Douglas-fir. All were planted to Douglas-fir and commercially thinned by ground-based equipment 14 years ago (1993). The thinned stands were similar (Table 1) in quadratic mean diameter (QMD), age, height, live crown height, trees per hectare, basal area per hectare, and stand density index (Reineke 1933, Curtis 1970).

A walking traverse of each stand was done to identify and select all damaged trees. Eighteen trees with mechanical damage in the lower bole through the cambium and with at least 0.09 sq m of damaged surface area (Table 2), caused by ground-based harvesting equipment from the earlier thinning, were identified and a subset of 11 of these trees used for this study. An additional 11 neighboring undamaged trees were identified as control trees. Control trees were of similar size with at least one tree between the control tree and damaged tree. All sample trees were in the dominant/co-dominant crown class.

The DBH and bark thickness at BH of each marked tree were measured. Bark thickness was determined with a Haglof barktax bark gauge. Four bark measurements were made before felling in cardinal directions and averaged for each tree. Wound depth was measured by projecting a reasonable undamaged surface for the tree with a taut diameter tape through the visual centroid of the damaged area and measuring depth to wound surface from the projected undamaged surface. In addition, width, length, and height above ground of the wound were measured and recorded from the visual centroid of the damaged area. Each marked tree was felled with the cut as close to the ground as possible. Measurement of crown height, crown width at the base of the live crown, and total tree height were measured once trees were felled.

The lower 1.6 meters of the bole of all felled trees was bucked out and tagged in the field. After the bole was cut out, an additional 100–200 mm disk was cut from the remaining log and the lower disk face was identified (Fig. 1). A similar sized disk was cut from the base of the

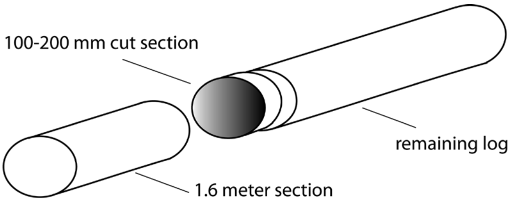

Fig. 1. Diagram showing the log sections used for the study. The 1.6 m bucked sections were transported back to the College of Forestry Forest Research Laboratory (FRL) along with the disks for dissection along with the disks.

live crown and identified. Sapwood was differentiated from heartwood using 2% alizarin red S stain (American Wood Preservers' Association 1999). All bucked sections were ground skidded to a designated landing and loaded onto a trailer for transport back to the College of Forestry Forest Research Laboratory (FRL) along with the disks.

The bucked sections were sawn lengthwise into approximately 25.4 mm thick boards using a Hudson Forest Equipment Inc. Oscar 28 manual portable sawmill. Lengthwise cuts on the damaged trees were aligned as closely as possible so that the resulting boards were oriented with their wide direction perpendicular to the wound face.

The opened surfaces of all board sections were visually inspected and the areas of decay, discoloration, sapwood, and heartwood were measured on the board upper surface in 100 mm increments for the length of the board. Sapwood and heartwood widths were measured on both the undamaged and damaged sides. Sapwood was differentiated from heartwood using 2% alizarin red S stain (American Wood Preservers' Association 1999).

Cross-sectional areas and volumes were computed for the decay, discoloration, sound wood, sapwood, and heartwood for each of the 100 mm sections for all boards from each log using an average end area formula:

$$\text{Volume} = \frac{A_1 + A_2}{2} \times (\text{Sectiondepth}) \times (100\ \text{mm}) \quad (1)$$

Where:
A_1 = Damage area diameter of one end of the 100 mm section
A_2 = Damage area diameter of the other end of the 100 mm section
Volume = Volume for each mapped section (decay, discoloration, etc.)
Sectiondepth = depth of each board, typically 25.4 mm

The volumes for each of the mapped areas were combined for all of the boards. Total log volume was the aggregate of all of the board volumes.

Each of the 100–200 mm cut disks were stained with 2% alizarin red S on the upper surface to differentiate sapwood and heartwood. Each disk was marked along the axes as near to the visual long and short dimensions as possible. Sapwood and heartwood dimensions (mm^2) were measured along these axes using a Mitutoyo digital caliper (0.01 mm). Sapwood and heartwood area were calculated from these dimensions. Individual growth rings were measured along these same axes from the pith outward and annual radial growth was determined for the 14 year periods both pre-thinning and post-thinning. Pre-thinning age was determined by counting rings back to the known year of thinning.

Prevailing winds for the study sites are from the south (180º). Values for wound angle to prevailing wound were modified by aspect transformation (Stage 1976, Stage and Salas 2007) for slope and wound aspect as:

$$X_4 = 4.1577 + \cos(a) \times (0.08070 \times s) + \sin(a) \times (0.08423 \times s) - 0.12634 \times s \quad (2)$$

2.2 Statistical Analysis

The statistical design and analyses for this study were planned to analyze the following attributes for damaged trees: 1) compartmentalization of damaged wood, 2) wood volume affected by wounding, and 3) differences in sapwood thickness on wounded and opposite sides of trees. In addition, damaged and undamaged trees were compared for 4) differences in radial increment for the 14-year period prior to damage and the 14-year period following damage, and 5) differences in ratio of crown base sapwood area to breast height sapwood area.

The analysis of compartmentalization was a qualitative macroscopic examination of sawn logs and a microscopic examination of changes in cell structure. A linear model for addressing objective 2 predicting affected wood volume % 14 years after initial tree damage was developed from a full model incorporating variables for tree size and wounding.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_8 x_8 + \beta_9 x_9 + e_i \tag{3}$$

Where:

y = Volume of affected wood as a percentage of the bole volume
x_1 = Basal area inside bark at breast height (m^2)
x_2 = Diameter inside bark at breast height (cm) DIB BH
x_3 = Length to width ratio of the wound measured through the visible centroid
x_4 = Height above ground level to the visible wound centroid (m)
x_5 = Depth of wound measured through the visible centroid (cm)
x_6 = Width of wound measured through the visible centroid (cm)
x_7 = Length of wound measured through the visible centroid (cm)
x_8 = Surface area of wound (cm^2)
x_9 = indicator variable for site
e_i = Error term for individual data points from the predicted regression

Objective 3 was addressed by the full linear model:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + e_i \tag{4}$$

Where:

y = Increase in sapwood radial distance opposite the damaged side(cm)
x_1 = Diameter at breast height (cm)
x_2 = Depth of wound measured through the visible centroid (cm)
x_3 = Surface area of wound (cm^2)
x_4 = Angle of the wound surface to the prevailing winds
e_i = Error term for individual data points from the predicted regression

Objective four was addressed by paired t-test. All P-values are computed as two-tailed unless noted otherwise. Key assumptions behind these comparisons included: 1) identified damage was a result of logging damage at the time of the thinning operation; and 2) identified compartmentalization was the result of logging damage.

3 Results

Data were collected on 236 boards sawn from the 22 butt log sections. Sixteen cross-sections were measured for each board for a total of 3776 cross-sections. All of the boards examined from the damaged trees had characteristic features that included (Fig. 2) a dark barrier-zone (wall 4) approximately 2 mm in width that had been formed at the point of damage (a). The material in this dark zone (Fig. 3) appeared heavily resinous and the zone was closely aligned with the vertical extent of the damage. Walls 1–3 were evident but not distinct. No compartmentalized walls were evident in the control boards.

The absence of a breech in wall 4 in any of the sample boards validates the reported effectiveness of this wall (Hockenhull 1974, Shigo and Marx 1977, Shigo 1984). Walls 2 and 3 also limited extension of damage beyond the wound, again supporting their effectiveness. Wall 1 however was least effective. Discolored and resin streaked tissues averaged 495 mm beyond the top edge of the wounds longitudinally (SE = 83 mm).

Tissues at the lateral margins of the wounded areas were easily distinguished macroscopically (Fig. 4). New wood tissue formed outside of the damaged area had the general appearance of burl wood and the cut surfaces were fairly resistant to liquid penetration suggesting a resinous nature. The heartwood/sapwood indicator Alizarin red S (indicator for calcium in living tissues) stain suggested this wood was similar to stained heartwood. Sapwood tissues adjacent to the wound maintained a typical appearance and sapwood chemistry as indicated by the same stain.

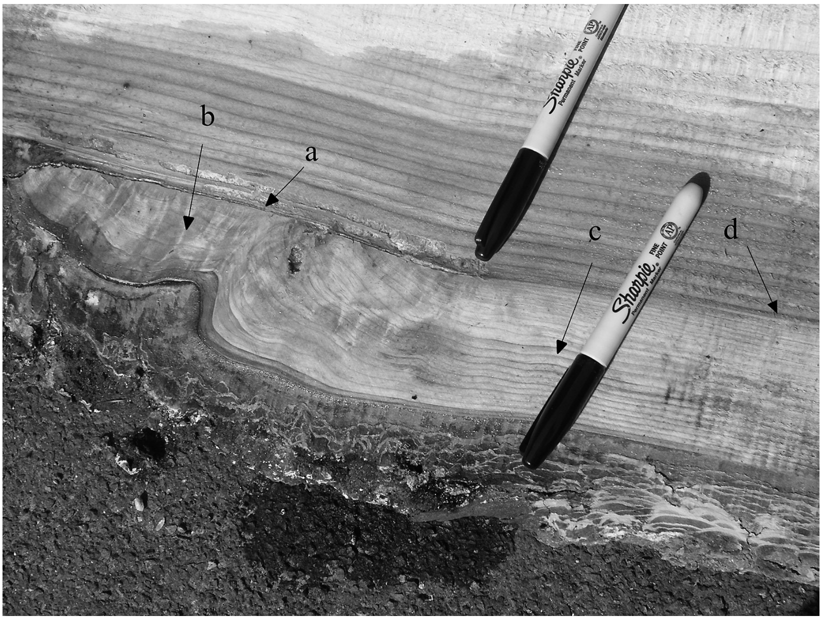

Fig. 2. Radial cross-section showing the sapwood area response following wounding. The dark-lined barrier zone can be seen at a. Arrow b shows the burl-like area produced following the damage. Arrow c shows the newer sapwood below the damage. A faint line at arrow d shows some extension of the barrier zone behind this region.

Fig. 3. Lumber section cut from the wounded area of a Douglas-fir log showing the 2 mm thick barrier zone produced following wounding.

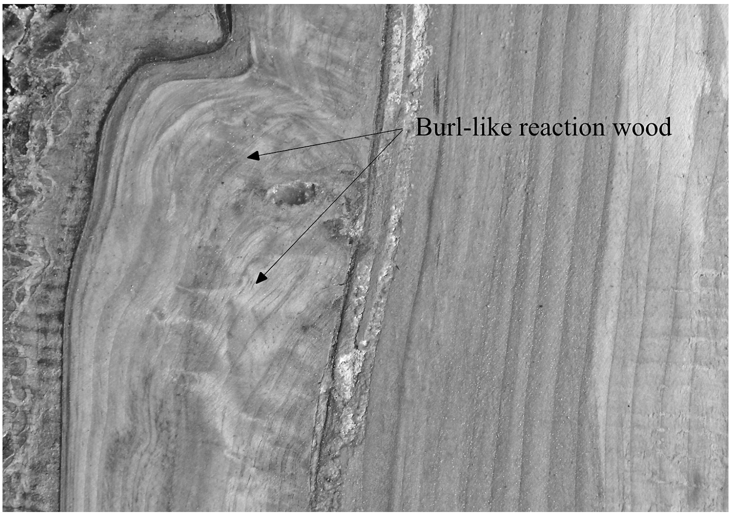

Fig. 4. Radial cross-section showing the burl-like wood formed by a Douglas-fir tree on the exterior of the barrier-zone following damage.

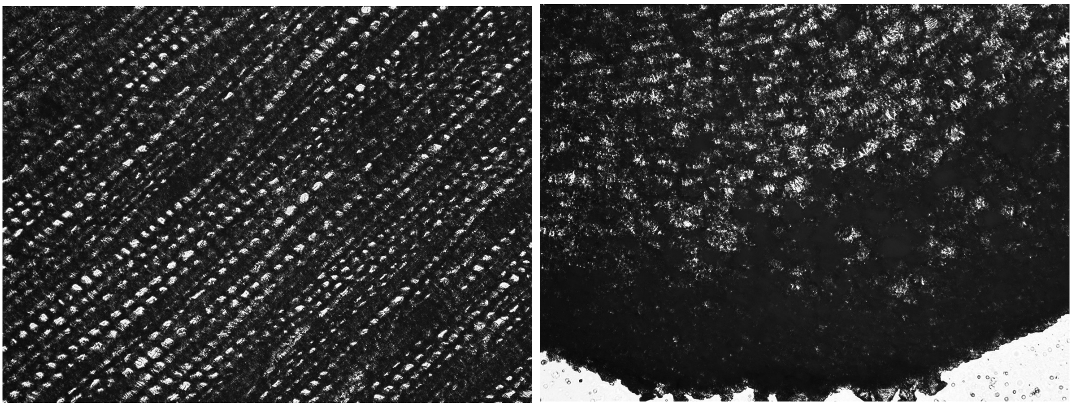

Fig. 5. Micrographs of transverse cross-sections cut from damaged and normal areas of wood in a Douglas-fir tree show clear tracheids in the undamaged areas (a) and resin-filled cells in the boundary of the damaged zone (b).

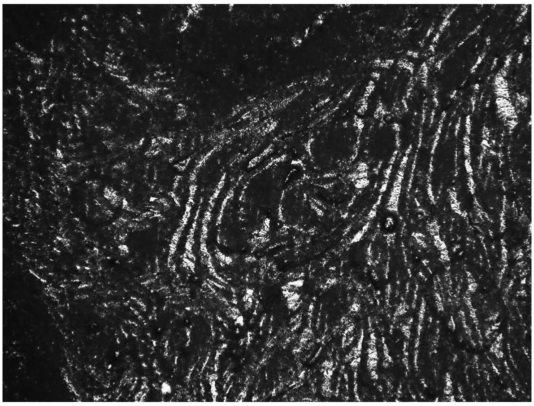

Fig. 6. Micrograph of transverse cross-sections cut from the burl-like reaction wood formed following damage to a Douglas-fir tree. Cells vary widely in shape, size, and arrangement. Some plugging is still evident.

Wood cells at the lateral margins of the wounded areas were also microscopically different from those formed prior to wounding (Figs. 5a, 5b and 6). Cell structure in the normal wood was typically unplugged and similar in size, shape, and structural arrangement. Wood cell structure in the post-wounded area, on the other hand, was quite diverse. Tracheids adjacent to the boundary zone were heavily resin filled while those outside this area were brownish-golden colored and appeared to be encrusted with crystalline deposits.

The effects of wounding on subsequently produced wood tissue included discoloration and burl-like tissue of the post-damage sapwood. Newly formed wood tissues were typically plugged and burl-like for 4–6 years following damage, becoming more normal in appearance and unplugged 5–7 years following damage.

This burl-like wood was produced as cambial initials reorganized around the wounded area. Wood in this zone would likely have dramatically different material properties, making it unsuitable for some engineering or aesthetic wood products. Average volume of affected wood represented 18.8% (95% confidence interval 10.9% to 26.7%) of the total volume of the lower bole.

Analyses of Eq. 3 residuals (SAS ver. 9.1) suggested model log transformation. Model comparison for best fit among 3 log transformations was determined from Furnival's index (Table 3) (Furnival 1961).

Model form:

$$\mathrm{Ln}(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_3 + \beta_3 x_4 \qquad (5)$$

$$\mathrm{Log}(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_3 + \beta_3 x_4 \qquad (6)$$

$$\mathrm{Sin}^{-1}(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_3 + \beta_3 x_4 \qquad (7)$$

$$\mathrm{Log}(y) = \beta_0 + \beta_1 \log(x_1) + \beta_2 \log(x_3) + \beta_3 (x_4) \qquad (8)$$

Table 3. Summary of Furnival's Index to determine best fit model for the prediction of affected wood volume as a result of damage during commercial thinning harvest. (Furnival 1961).

Computations	Eqn (5)	Eqn (6)	Eqn (7)	Eqn (8)
RMSE	0.4253	0.1846	4.3153	0.1951
$\sum \log [f'(Y)]^{-1}$	10.4819	13.101	4.6800	13.101
$(\sum \log [f'(Y)]^{-1})/n$	0.9527	1.191	0.4255	1.191
antilog	8.9687	15.524	2.6635	15.524
Index	8.7829	6.5985	26.4656	6.9739

Log Y transformation (Eq. 6) produced slightly better fit results than log/log transformation (Eq. 8) and is easier understood. Final model results are: (SD in parentheses)

$$\begin{array}{l} \mathrm{Log}(Y) = 2.121 - 0.046\,(x_1) + 0.025\,(x_3) + 0.000087\,(x_4) - 0.116\,(x_9) \qquad (9) \\ \qquad\qquad (0.810) \quad (0.039) \qquad (0.052) \qquad (0.00015) \qquad (0.419) \end{array}$$

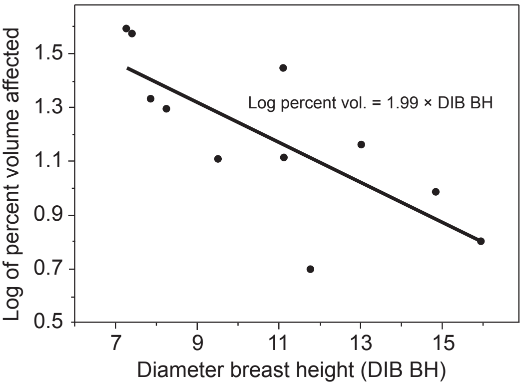

Fig. 7. Linear regression of DIB BH on log of percent volume affected.

The model explained about 72% of the variability in affected wood volume as a percentage of total bole volume (p = 0.02). The best single predictor of volume affected was DIB BH explaining over 57% of the variability in percentage volume affected (Fig. 7). Wound area alone explained slightly more than 10% of the variability while depth of wound explained less than 1% of the variability. However depth of wound combined with DIB BH explained an additional 4.7% (62.3%) of the variability while surface area added an additional 5.6% (63.2%) when combined with DIB BH. Although site was not significant in the model (p = 0.40) it was left in to incorporate the study design.

A revision of the model form was made to incorporate the multiplicative effects of X_3 and X_4 on volume by creation of a surrogate for wound volume, X_5. The new model form was:

$$y = \beta_0 + \frac{\beta_1 x_5}{160\ \mathrm{cm} \times x_1^2} \qquad (10)$$

Measured wound volume was not uniform in shape within the boles however and variability with calculated volume (X_5) was extreme (SE % > 600). Attempts to incorporate the surrogate variable in other model forms were equally weak with the surrogate dropping out first in each attempt.

Table 4. Summary pre-thinning and post-thinning annual radial increment data for 14-year periods.

	Pre-thinning annual radial increment (mm)		Post-thinning annual radial increment (mm)	
	Damaged	Control	Damaged	Control
Mean	3.81	3.56	2.54	3.05
SD	1.52	1.52	1.02	1.27
N	14	14	14	14
Range	1.27–6.35	1.024–6.60	1.27–4.57	0.51–5.59

Sapwood width on the opposite side of the tree from the damage averaged about 15 mm (SE = 2.3 mm) greater than sapwood width on the damaged side along the length of the bole. Average sapwood radial distance at the point opposite the centroid of the damage was 36.3 mm (95% C.I. 6.3 mm to 66.3 mm). The full model for prediction of increase in sapwood radial distance at the centroid was:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + e_i \qquad (11)$$

Where:

y = Average difference in sapwood width between the damaged side and undamaged sides (cm) along the bole.

x_1 = Diameter at breast height (cm)

x_2 = Depth of wound measured through the visible centroid (cm)

x_3 = Surface area of wound (cm^2)

x_4 = Angle of the wound surface to the prevailing winds

e_i = Error term for individual data points from the predicted regression

The wound depth variable was not significant to the full model (P = 0.48) and was dropped. The transformed aspect variable was not significant in the reduced model (P = 0.56) and was removed. Further reduction of the model showed no significance for the DBH variable (P = 0.35). The final reduced model showed convincing evidence for the wound area variable (P = 0.003). The final model was therefore: (SD in parentheses)

$$y = -1.004 + 0.00076 \text{ (wound area in cm}^2\text{)} \qquad (12)$$
$$(2.25) \quad (0.0006)$$

The model explained slightly more than 65% of the variability (RMSE = 0.749) in increased sapwood width opposite the damaged side (p = 0.00096).

Paired t-test of radial increment for the 14-year period before and after thinning for damaged and undamaged trees was done (Table 4). Average radial increment before damage showed no differences between damaged and undamaged trees (P = 0.26). Average radial increment after damage also showed no differences between damaged and undamaged trees (P = 0.56).

The post-damage ratio of cross-sectional sapwood at the base of the live crown to sapwood at breast height was computed for the control and damage trees. Control trees averaged 0.56 and damage trees averaged 0.65. A t-test showed no significant differences in these ratios (P = 0.27) indicating that wounding did not appreciably affect the overall ratio of cross-sectional sapwood area at the base of the live crown to sapwood at breast height.

4 Discussion

Response of younger-age Douglas-fir to mechanical injury in this study appears to follow the general models of barrier zones (CODIT) and reaction zones. Wounded trees developed a heavily resinous zone analogous to Shigo's wall 4 that appeared to exclude any decay or discoloration that was present in adjacent tissues of the boards examined. Wood tissue comparable to walls 1–3 (also Shain's reaction zones) were not nearly as distinct as reported in other species, primarily less-resinous hardwoods. Wood tissues in these areas were heavily streaked axially with resins and the walls were nearly always poorly defined. Similar streaking has been reported in hemlock and balsam fir and is believed to constitute a compartmentalized zone (Tippett et al. 1982). The presence of tissues similar to walls 2 and 3 suggest that the trees were successful at limiting damage beyond the wound. Wood tissue corresponding to wall 1 appears to have been the least effective at limiting damage in the axial direction response. While walls 2, 3, and 4 showed no signs of breaching by either decay or discoloration, the more serious consequence from wounding in this study was the amount of vertical discoloration in the sapwood, primarily from resin-streaking, extending on average 49.5 cm vertically above the top of the wounds. This concern has been previously noted (Vasiliauskas 2001), particularly for many of the conifer species where susceptibility to decay is relatively low (Aho 1960, Vasiliauskas and Pimpe 1978). These results appear to be consistent with the reported strengths of each wall (Shigo 1975, 1976). In addition, the relative effectiveness of the responses in this study support earlier studies of sapwood discoloration in inoculated Douglas-fir (Deflorio et al. 2007).

The heavy vertical streaking is consistent with reported increases in the production of parenchyma cells and polyphenol accumulation (Tippett and Shigo 1981) following cambial injury. The polyphenol production is considered to be important in development of the barrier zone (Shortle et al. 1978) and is generally followed by production of tangential traumatic resin ducts (Fahn and Zamski 1970). Resin production and polyphenols are linked to restriction of microorganisms (Rishbeth 1972, Tippett and Shigo 1981).

The active formation of compounds immediately following injury seals off water conducting elements, however, it is not related to limiting pathogen entry but is instead a tree reaction to stop air penetration into the vessels and protect the water conducting system. The lack of evident decay may be due to the reported secondary inhibition of fungal growth by these compounds (Boddy and Rayner 1983, Schmidt 2006).

4.1 Affected Wood Volume

Almost 19% of the lower bole volume in damaged trees was affected by discoloration and secondarily by structural changes. However, it would be more reasonable to consider the volume loss as a percentage of a longer log length as dictated by mill practice. For the purposes of this discussion, a conventional 3.7m board was used as the basis for determining value loss although, it is recognized that mill practices regarding bucking lengths can be quite variable, especially with regard to board-foot volume practices.

Determination of economic loss based on discoloration should be based on lumber recovery rather than mill scaling since the extent of the discoloration will not be known until boards are sawn. Discolored wood in the butt logs can still meet a utility grade and therefore return value (West Coast Lumber Inspection Bureau 2004). This grade allows for staining and is based on utility value rather than appearance. A reasonable method for estimating the impacts of damage might be based on current price ratios between select merchantable and utility grades multiplied by the calculated volume based on the prediction model.

Assume for example, a 3.7 m log (trim excluded) that is 45.7 cm in the large end diameter and 43.1 cm in the small end diameter with the average 19% affected volume. 2008 U. S. lumber prices for utility grade were about 79.4% \$58/m^3 of the price for #1 or better grade at \$71/m^3. The scale for this log is about 0.33 m^3, therefore the value of this log undamaged is \$23.80. Reduction of 19% of the milled volume or about 0.06 m^3 to the lower grade results in a value of \$23.00 or a reduction in value of about 3.5%.

One alternative to this example would be to selectively trim the damaged boards to the higher grade and either discard or chip the damaged ends. Because the wound is generally at the lower 0.6 m of the butt log, damage loss may then be minimized by trimming boards in the manufacturing process. For example, bucking a 3.7m log with damage in the first 0.6 m will yield 3.7 m boards that are no. 1 or better grade except for the boards in the damaged area. Trimming the 0.6m damaged boards will still yield 3.1m no. 1 or better boards as opposed to 3.7 m utility grade boards. Using this alternative, the percentage volume loss is about 3% or 0.01m^3 and the value loss then is just over 2.5%. Conventional practices typically buck the damaged end off and leave it in the woods. However, this practice would result in an estimated loss of over 14% of the volume or 0.05m^3 of the log and a value reduction of just less than 11% (Table 5).

Table 5. Summary table showing changes in percentage volume and value from bucking alternatives of the example log. Modification of traditional bucking practices could result in value recovery of 7.5–8.5% of the lower butt log.

	Volume lost	Value lost
Traditional Bucking	14%	11%
Milled as-is	0%	3.5%
Selective Trimming	3%	2.5%

4.2 Sapwood Radial Distance

Initial sapwood mapping revealed that sapwood width in damaged trees was disproportionately larger opposite the wounded side of the tree bole. Modeling these data for effective volume increase showed a fairly strong relationship with wound size. The increase was not related to prevailing wind, suggesting that the increase was in response to wounding.

Although tree boles serve both physiological and mechanical support roles (Long et al. 1981), the lack of correlation between increase in sapwood and prevailing winds suggests that the response was not in support of bending stresses typically due to wind (Assmann 1970), but instead a response to maintain a physiological balance between stem xylem cross-sectional area and transpiring foliar surface area or mass (Shinozaki et al. 1964, Kline et al. 1976, Rogers and Hinckley 1979, Waring et al. 1982). The lack of differences in radial increment between damaged and undamaged trees after thinning appears to support this. Sapwood area lost to wounding appears to be the result of a slowdown in conversion of sapwood to heartwood suggesting the priority of maintaining the physiological balance with the crown area.

5 Conclusions

Effects of wounding on the growth response of younger-aged Douglas-fir are not a serious concern over short term rotation scenarios. However, value loss through grade reduction of the affected portion of the damaged tree can be significant. Study trees that had been damaged contained very distinct and heavily resinous barrier zones on the xylem surface at the time of wounding, but the other three walls described in compartmentalization were not as distinct. Heavy resin streaking however was evident in the longitudinal direction. Wounded trees showed an increase in sapwood radial distance opposite the wound, such that sapwood cross-sectional area was not significantly different from control trees 14 years after damage, suggesting a response that wounded trees re-establish sapwood area necessary to provide physiological support to the live crown.

While wounding does not appear to affect radial growth, wood quality and volume are adversely affected. Model results predict about 19% lower bole volume affected by wounding, primarily in reduced grade. The example presented illustrates how typical bucking practices would result in significant value loss in the lower log. This value loss may be mitigated by suggested alternatives in both bucking and milling of the damaged log. However, this does not suggest that mitigation measures may absolve the need to prevent damage from occurring. Certainly, while outside the scope of this work, residual tree damage should be avoided from the perspective of worker safety and work production and quality. Within the scope of this work, a number of areas still need investigation including: a) longer-term affects beyond short rotation intervals, b) market changes affecting lumber grade valuation, c) decay and discoloration spread as affected sapwood areas transition to heartwood, and d) longer-term effects on stand conditions, particularly where forest health is concerned.

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