Temporal change in wood quality attributes in standing dead beetle-killed lodgepole pine

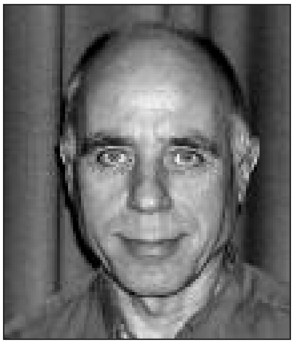
by Steen Magnussen[1,2] and Dave Harrison[1]

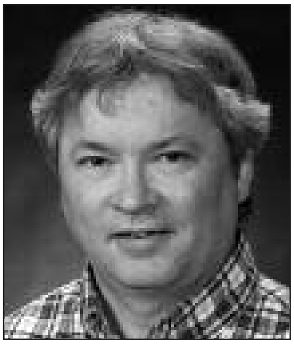
ABSTRACT
The number and size of checks, wood moisture content, extent of blue-stain, rot and decay was examined by stem analysis in 360 mature standing beetle-killed lodgepole pines. Trees came from three areas (Burns Lake, Quesnel, and Vanderhoof) in Central British Columbia. Each area was represented by 14 to 16 sampling areas (stands) distributed evenly across three soil moisture regimes (dry, mesic, wet). Year of death was estimated from tree ring-analysis, local knowledge and insect and disease survey maps. An approximately equal number of trees had been dead for one or two years, three or four years, or for five or more years. During the first five years since death by beetle attack the number of checks per tree increased from 2.5 to 10.2 and the average depth of checks increased from 4.3 cm to 5.1 cm. Checks were deeper, wider, and longer on the drier sites than on mesic and wet sites. Moisture content of sapwood and heartwood was near the fibre saturation point (ca 30%) one year after death and continued to decrease at a rate of approximately 1.7% per year. Both the incidence and the extent (relative to basal area) of rot and decay increased significantly with time since death. All trees had an extensive blue-stain discoloration. Deterioration of wood quality was fastest during the first two years after a beetle attack.

Key words: wood checks, moisture content, blue-stain, wood quality, spiral grain, bark beetle

RÉSUMÉ
Le nombre et la taille des blessures, le niveau d'humidité dans le bois, l'étendue de la décoloration, de la carie et de la pourriture ont été étudiés lors de l'analyse des tiges effectuées dans 360 peuplements mûrs ravagés par le dendroctone du pin lodgepole encore sur pied. Les arbres provenaient de trois régions du centre de la Colombie-Britannique (Burns Lake, Quesnel et Vanderhoof) Chaque région était représentée par 14 à 16 zones d'échantillonnage (peuplements) répartis uniformément parmi trois régimes hydriques du sol (sec, mésique et humide). L'année de la mort a été estimée par l'analyse des anneaux des arbres, les informations locales et les cartes d'inventaire des insectes et des maladies. Un nombre approximativement égal d'arbres étaient morts depuis un ou deux ans, depuis trois ou quatre ans ou depuis cinq ans et plus. Au cours des cinq premières années suivant la mort causée par le dendroctone, le nombre de blessures par arbre a augmenté de 2,5 à 10,2 et la profondeur moyenne des blessures est passée de 4,3 à 5,1 cm. Les blessures étaient plus profondes, plus larges et plus longues sur les stations sèches que sur les stations mésiques et humides. Le niveau d'humidité dans l'aubier et le bois de cœur était près du niveau de saturation des fibres (30 %) un an après la mort et continuait de diminuer à un taux d'environ 1,7 % par an. Tant l'incidence que l'étendue (par rapport à la surface terrière) de la carie et de la pourriture ont augmenté significativement en fonction du temps écoulé depuis la mort. Tous les arbres montraient un important bleuissement du bois. La détérioration de la qualité du bois était plus rapide au cours des deux ans suivant les ravages de l'insecte.

Mots clés : blessures d'arbres, niveau d'humidité, bleuissement, qualité du bois, texture spiralée, dendroctone du pin


Steen Magnussen


Dave Harrison

Introduction

British Columbia is experiencing the most severe epidemic outbreak of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) in recorded history. Lodgepole pine (*Pinus contorta* var. *latifolia* Dougl. ex Loud) is the primary host. It is estimated that since the late 1990s the beetle has killed more than 300 million m^3 of lodgepole pine timber[3]. In 2006 newly infested areas covered 9 million ha. It is anticipated that the current epidemic will decline to endemic levels by 2010; at that time the mature lodgepole pine stands will have been severely decimated.

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[3] www.for.gov.bc.ca/hfp/mountain_pine_beetle

[1] Natural Resources Canada, Canadian Forest Service, 506 West Burnside Road, Victoria, British Columbia V8Z 1M5.
[2] Corresponding author. E-mail: steen.magnussen@nrcan.gc.ca.

In response to the severity and spatial extent of the infestation, there has been a sharp increase in the harvest of dead standing beetle-killed trees. Several wood attributes of standing beetle-killed trees change with time since death and they are often sufficiently different from those of live trees to warrant the concern of those who handle and process them (Byrne *et al.* 2005a, b; Woo *et al.* 2005; Orbay and Goudie 2006, Trent *et al.* 2006, Chow and Obermajer 2007). The sapwood of infested trees shows discoloration by blue-stain fungi introduced by the beetle a few weeks after the initial attack, and the moisture content of sapwood and heartwood is known to decrease below fibre saturation with time since death (Woo *et al.* 2005). Checks created by the release of drying stress are also much more frequent in standing dead beetle-killed trees than in live trees. Finally, as time since death passes the risk of a secondary attack by either wood-boring beetles, infections by rot- or decay-causing fungi, or damage work by insect-seeking birds and mammals increases sharply (Byrne *et al.* 2005a, Kim *et al.* 2005, Lewis and Hartley 2005, Trent *et al.* 2006).

The sheer magnitude of beetle-killed dead standing wood volumes expected to be harvested over the next few years makes it important to understand how time since death and site factors impact wood quality. Woo *et al.* (2005) found that sapwood and heartwood from beetle-attacked trees had a substantially lower moisture content and specific gravity than sound wood (see also Byrne *et al.* 2005b, Harrison 2006). Infested sapwood had significantly lower concentrations of extractives, lignin, and hemicellulose, and was more permeable to solvents. These changes are known to influence the quality of both wood and fibre products. Chow and Obermajer (2007) confirmed a rapid decline in moisture content with time since death, which calls for specific handling and drying procedures for beetle-killed wood.

Blue-staining of the sapwood following a beetle attack is caused by *Ophiostoma* spp. fungi for which the beetle is a vector (Byrne *et al.* 2005a, Kim *et al.* 2005, Zhu and Myers 2006). Mechanical properties and rot resistance of blue-stained lodgepole pine wood is at par with properties of non-stained wood (Byrne and Uzunovic 2005, Lum *et al.* 2006), and Kraft pulp production yield and costs are not adversely affected (Zhu and Myers 2006). Blue-stained wood has been mistakenly considered as being in the first stages of decay (Byrne *et al.* 2005a), and mechanical pulp prepared from blue-stained wood may need additional bleaching before it is considered acceptable. The extent and type of decay in standing blue-stained beetle-killed trees is generally not much different from that of non-attacked trees, at least during the first years following the attack (Byrne and Uzunovic 2005, Kim *et al.* 2005).

Checks in beetle-killed pine constitutes a potential serious loss in volume recovery and value (Byrne *et al.* 2005a, Orbay L. and Goudie 2006). Checks as deep as several centimetres and up to several decimetres in length can develop within a year after the tree dies (Lewis and Hartley 2005, Harrison 2006). Checks continue to expand in both numbers and size with time since death. Orbay and Goudie (2006) found the volume recovery value was a simple linear function of check severity index (no. of checks × relative check depth × relative check length). The above-cited studies indicate that a volume loss of 5% two years following attack would not be unusual. Veneer recovery rates are also adversely affected (Byrne *et al.* 2005a, Wang and Dai 2005). Site conditions (wet, mesic, dry), weather conditions, handling and mill operations attenuates the effect of checks on yield and value produced (Byrne *et al.* 2005a, Eng *et al.* 2007).

The objective of this study was to assess the effects of site conditions and time since death on *i*) checking, *ii*) blue-stain, *iii*) rot and decay, and *iv*) moisture content of standing beetle-killed lodgepole pine. A large number of sample trees (360) taken from three areas, each represented by 15 sites with contrasting soil moisture regimes (dry, mesic, wet) located in the epicentre of the current epidemic allow us to quantify practically relevant effects.

Material and Methods

During the summer of 2006, 360 beetle-killed lodgepole pine trees from 45 sites were felled in north-central British Columbia and bucked into 2.5-m lengths with stem analysis discs taken for detailed measurements of moisture content, checking, blue-stain, and rot and decay. Stem discs were taken at stump height (0.3 m), breast height (1.3 m), and at 2.5 m intervals from stump. A final disc was taken at a location where the under-bark diameter was approximately 10 cm. The year of beetle attack (*YA*) and death of the trees was estimated using local knowledge, forest insect and disease survey maps, and dendrochronology techniques. Estimates ranged from one to eight years. In general, the uncertainty of *YA* increases with *YA*. In our assessment *YA* values below 2 are error-free. At the other end, we acknowledge that the error of a $YA = 8$ estimate could, in some circumstances, be as high as two years. Tree age was not determined.

Sites were located in three areas of Central BC in UTM grid 10 in the sub-boreal spruce (SBS) Biogeoclimatic zone. A total of 45 sites were located the Quesnel (16), the Vanderhoof (14), and the Burns Lake (15) area. The 16 sites in the Quesnel area were located between Northings 5846895 and 5899403 and Eastings 499264 and 579804. For the Vanderhoof area the 14 sites were between Northings 5963819 and 6016804 and Eastings 374893 and 389510. Corresponding numbers for the 15 sites in the Burns Lake area were 5957415 to 6027704, and 318004 to 694616. Between five and 14 trees—with an average of eight—were sampled per site. Sites and trees were selected to conform to a uniform distribution with respect to the following three classes: time since attack $YA = \{1-2, 3-4, \geq 5\}$, three diameter at breast height classes (12.5 cm – 22.5 cm, 22.5 cm ≥ 32.5 cm, and ≥ 32.6 cm), and three classes of soil moisture regime (dry, mesic, and wet). A total of 121 trees were in the first *YA* class, 119 in the second, and 120 in the third. Tree heights varied from 15.6 m to 34.2 m (mean: 23.9 m, standard deviation 3.2 m). On each site, sample trees were selected from within an approximately 100 × 100 m (1.0 ha) area located at least two tree-lengths from any stand edge or openings.

A large number of site (18), tree (22), and disc (15) attributes measured in the field and the laboratory. A complete listing is available from the corresponding author upon request. All disc measurements were carried out in the field within two to three hours of felling. Discs were protected from sun and rain until they could be processed. Increment cores for determining *YA* were collected from 22 live trees in the Quesnel area, and 21 in the Vanderhoof area. No suitable live tree was located in the Burns Lake Area.

Statistical analysis and data processing

The main focus of the statistical analyses was to quantify the effect of *YA* (time since attack/death), soil moisture regime (*SMR*) and site and tree attributes on: 1) the number, depth and width of checks, 2) the moisture content of sapwood and heartwood, 3) the incidence of rot and extent of decay, and 4) the extent of blue-stain. Most analyses were done on a per-tree basis (total or average) or for observations pertaining to the first 2.5 m of the stem. When the attribute of interest depends on the stem location the analyses were done on a per-disc basis. The effects considered for both *YA* and *SMR* include interactions with observed area, site, tree, and disc attributes. All available area, site, and tree attributes were considered for inclusion as predictors of the attribute of interest in a given model. However, predictors that were non-significant at the 0.05 level of statistical significance were dropped from a model via a backward stepwise elimination procedure based on *F*-tests (Draper and Smith 1981). We employed generalized linear and non-linear mixed models with site considered as a random effect and trees within a site as equal-correlated random variables (McCulloch and Searle 2001). When disc data were used as the dependent variable, the model was extended to include the disc as a random variable with a first-order autoregressive within-stem covariance structure (Christensen 2001). For proportions (or percent data) and binary data we used a logit link function between the data (y) and the expected value (μ). For count data a Poisson model (Lawless 1987), a zero-inflated Poisson model (Ridout *et al.* 2001), and a negative binomial model (White and Bennetts 1996) were considered. A mixed-effects logistic model with sites as random effects and area, *YA, SMR*, and spiral grain as fixed effects was entertained for the estimation of conditional and marginal odds ratio of rot/decay incidence. The significance of the difference between two fixed effects was assessed with a likelihood ratio test.

We allow for over-dispersion in attributes expressed as counts, and proportions (percent) by including a gamma–distributed random variable acting as (constant) variance multiplier (McCulloch 1997). In models with random effects of site we present conditional estimates (COND) that apply to a typical site (mode) for which the random site effect is zero. We also show population averaged or marginal (MARG) estimates. They apply to a regional inference across a large number of stands/sites.

Throughout, Akaike's corrected information criterion, AIC_c (Akaike 1977, Vaida and Blanchard 2005) was used as guide for choosing the final model.

Given the inexact nature of *YA* and the fact that we have no prior expectation of a specific trend in the dependent variable across values of *YA*, we treated *YA* as a categorical variable with five nominal levels (*YA* = {"1", "2", "3", "4", "5+"}), i.e. a constant off-set from the general mean was estimated for each distinct *YA* value. The sum of the estimated *YA* effects sums to zero. We formed various linear contrasts of *YA* effects and tested them with a Wald's test for significant deviations from zero (Rencher 1995). A similar procedure was followed for tests of significant *SMR* effects. To summarize a trend that appeared linear we estimated, by generalized least squares, the estimated slope of the trend.

Checks

It was assumed that each check registered on a disc was independent of all other checks recorded for the same tree. We also assume that there were only a few minor (missed) checks between extracted discs. In short, the total number of checks observed on the discs is assumed to be close to but less than the actual number of checks. Large trees had more checks on extracted discs than smaller ones. Therefore, our analyses used an estimate of the surface exposed to bark-beetle attack as a covariate to adjust for tree size effect. The exposed surface area was computed from the disc measurements assuming that the shape of each stem section was that of a cone-frustum (Avery and Burkhart 1983). Volume-weighted tree averages of check size (depth and width) and their variation were calculated by standard methods.

To estimate the potential loss of sawn timber wood volume, we computed for each tree a relative check depth as a volume-weighted average of the ratio of the depth of a check to the under-bark diameter of the disc. On each disc, the wood from the cambium to 1.1 times the maximum check depth was considered potentially lost for sawn timber. The area of this loss was computed for each disc and a volume-weighted relative basal area loss was computed for each tree. A relative index of a potential log-volume loss was also obtained for each tree. If, for a given stem segment, the under-bark diameter of a disc was ≥ 12.5 cm but the diameter of a check-free core was less than 12.5 cm, the segment was considered unsuited as a saw-log. Again, 1.1 times the maximum check depth on a disc was used to delineate a check-free core. The proportion of log volume potentially lost due to checks was then computed as a volume-weighted average for each tree.

Moisture content (MC)

Nine *MC* measurements were taken on each disc with a Delmhorst J-2000 meter: at the pith and in the middle of the sapwood and heartwood at each cardinal direction. The point of measurement was moved if needed to avoid knots. A large number of readings were cross-checked with a second meter. Moisture content values obtained with the two meters were consistently within 1.0% of each other. Calibration measurements on 14 oven-dried discs revealed a systematic bias of the two meters of -2.1% and -2.4%, respectively. This bias persists in the results reported here. Since the meter readings were truncated to the interval from 6% to 40% it was necessary to address the impact of this censoring process. About 8% of the readings were recorded as 40% while only one was recorded as 6%. Inspection of histograms of moisture readings suggested that a reading of 40% should be transformed to a uniform distribution between 40% and 50% for sapwood and 40% and 45% for heartwood *MC*. This transformation was achieved by adding a random term drawn from a uniform distribution on the interval [0%, 10%] in the case of sapwood, and from [0%, 5%] in the case of a heartwood. No attempt was made to address the lower bound censoring. Sapwood and heartwood moisture readings were averaged per disc before analysis. A disc-level analysis was pursued due to the effect of stem position on *MC*.

Decay and rot

The type, location (heartwood, sapwood) and extent (area) of rot and decay were classified and measured on each disc according to a protocol established by the BC Ministry of Forests and Range. The sample sizes are not sufficiently large to provide a reasonable statistical power for an analysis by type; decay (rot) types have therefore been pooled.

Blue-stain

The width of blue-stain was measured on each of four disc quadrants and the blue-stained area estimated in percent. A volume-weighted tree average of the ratio of blue-stain width to stem radius under-bark was computed. A volume-weighted estimate of the blue-stained percent of the stem cross-sectional area was also obtained for each tree.

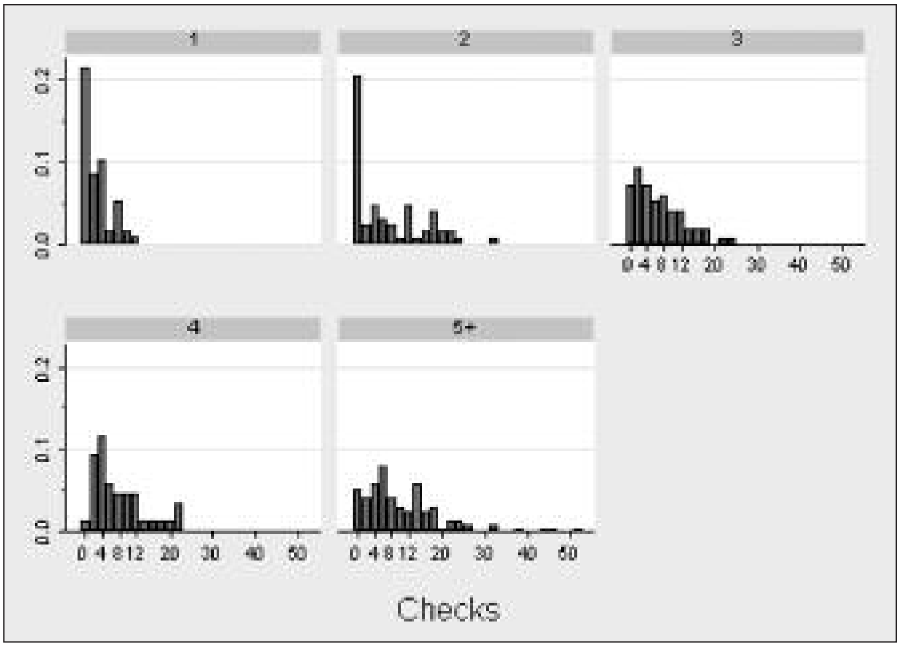

Fig. 1. Frequency distribution of the number of checks per tree by YA status (1, 2, 3, 4, 5+).

Results

The observed number of checks per tree from a given area and year of attack (*YA*) followed a distribution that resembled a negative binomial more than a Poisson or a zero-inflated Poisson distribution. As *YA* increases, the proportion of check-free trees decreases sharply and the distribution of checks per tree becomes increasingly right-skewed (Fig. 1). In *YA* = 1 the upper 95% limit was seven checks per tree and for *YA* ≥ 2 it varied between 17 and 25 depending on *YA* and area. The maximum number of checks on a tree was 52. A negative binomial model for the expected number of checks per tree is given in Eq. [1].

$$E\left(\#_{checks} \mid site = j, YA\right) = Exp\left[\mu + \nu_j + \beta_{spiral}\delta_{spiral} + \beta_{surf}x_{surf} + \alpha_{YA}\right]. \quad [1]$$

where μ is the overall specific mean, ν_j is a random effect of the *j*th site, β_{var} is a regression coefficient for variable "*var*," δ_{spiral} is an indicator variable for spiral grain (no = 0, yes = 1), x_{surf} is the stem surface area of a tree in m^2, and α_{YA} is the effect of *YA* in year *i* after death. For a negative binomial distribution $1/(1 + \nu_j)$ is distributed as a Beta(*r,s*) random variable. To compute stem surface area we assumed the shape was that of a cone. After including stem surface area as a predictor the stem diameter at breast height (*DBH*) was no longer a significant predictor on its own ($P = 0.979$). On their own *DBH* and tree height were both highly significant as predictors.

Sites influenced the number of checks but with no clear relationship to *SMR* ($P > 0.45$) or any other recorded site attribute. The number of checks per tree was proportional to its exposed stem surface (*SURF*), and significantly higher in trees with spiral grain. *YA* = 1 trees had the lowest number of checks. After adjusting for effects of *YA*, *SURF*, and spiral grain, the influence of area was non-significant.

Conditional (COND) and marginal (MARG) maximum log-likelihood estimates (McCullagh and Nelder 1989) of the model coefficients are in Table 1 with estimated standard errors. The estimated difference between *YA* = 1 and *YA* = 2 effects were about 50% smaller for COND than for MARG

Table 1. Effect sizes for the logarithm of the expected number of checks per tree. See [1] for details. Standard errors (s.e.) of the estimated effect sizes are computed with sites as random effects and trees within a site as correlated random effects.

	Whole Tree				First 2.5 m of Stem			
	COND	s.e.	MARG	s.e.	COND	s.e.	MARG	s.e.
Mean	-0.42	0.21	-0.42	0.26	-2.20	0.39	-1.00	0.32
Tree surface × 10	0.21	0.02	0.24	0.03	-0.00	0.00	-0.00	0.00
Spiral grain	0.59	0.10	0.54	0.13	2.56	0.22	2.12	0.18
YA=1	-0.81	0.22	-0.66	0.26	-0.80	0.45	-0.73	0.42
YA=2	-0.41	0.20	-0.04	0.23	0.52	0.32	1.10	0.31
YA=3	-0.08	0.16	0.04	0.21	0.03	0.34	0.26	0.32
YA=4	0.13	0.17	0.02	0.22	0.18	0.32	0.56	0.32
YA=5+	-0.03	0.15	-0.08	0.21	-0.13	0.30	0.53	0.29

Table 2. Effect sizes for spiral grain, *SMR*, and *YA* on check size. *CD* = check depth, *CW* = check width. Standard errors of effect sizes are in parentheses. All results are for volume-weighted whole tree averages. Analysis is based on trees with at least one check.

	CD (cm)	s(*CD*)[a] (cm)	*CW* (cm)	s(*CW*)[a] (cm)
Mean	5.2 (0.3)	1.9 (0.2)	0.32 (0.03)	0.16 (0.02)
Spiral grain	0.7 (0.3)	0.4 (0.1)	0.09 (0.02)	0.04 (0.01)
Mesic and Wet	-0.6 (0.3)	-0.2 (0.2)	-0.08 (0.03)	-0.03 (0.02)
YA = 1	-1.3 (0.5)	-0.8 (0.2)	-0.10 (0.03)	-0.06 (0.02)
YA = 2	-1.2 (0.4)	-0.6 (0.2)	-0.09 (0.03)	-0.04 (0.03)
YA = 3	-0.3 (0.4)	-0.4 (0.2)	-0.05 (0.03)	-0.05 (0.02)
YA = 4	-0.3 (0.4)	-0.5 (0.2)	-0.02 (0.04)	-0.03 (0.02)
YA = 5+	-0.6 (0.4)	-0.2 (0.2)	-0.03 (0.03)	0.00 (0.02)

[a] average within-tree standard deviation

due to the temporal increase in the among-site variation of the number of checks per tree. A model limited to the first 2.5 m of the stem would have indicated a much larger increase in the number of checks between *YA* = 1 and *YA* = 2 and impact of spiral grain. The among-tree variation within a site was substantial (coefficient of variation ≈ 170%).

Spiral grain was the single most important factor influencing the number of checks on a tree (Table 1). Close to 27% of the trees had spiral grain (47% in Quesnel, 14% in Vanderhoof, and 19% in Burns Lake). Trees with spiral grain had about 1.8 (MARG/COND) times as many checks as trees without spiral grain. For the first 2.5 m of the stem, this ratio was 13 (COND) and 8 (MARG). There was no important interaction between *YA* and spiral grain. Overall, the number of checks per tree would increase by about 2% (COND and MARG) for every 1 m^2 increase in stem surface area.

YA had a significant effect on the number of checks per tree (Table 1). *YA* = 1 trees had an average of 2.5 (± 3.1) checks compared to 8.1 (±8.1) for *YA* > 2 trees ($P < 0.001$). Also, the number of checks in *YA* = 2 trees was significantly lower (about 33%) than in trees with *YA* > 2. For the first 2.5 m of the stem the results were less clear.

The proportion of check-free trees declined by about 25% (±7%) for an increase of one in *YA*. While 42% (± 5%) of the trees were check-free in *YA* ≤ 2 no more than 10% (± 2%) qualified when *YA* > 2 ($P < 0.001$). Sites explained about 45% of the variation in the proportion of check-free trees. Absence of checks on the lower 2.5 m of the stem did not seem to be governed by factors beyond spiral grain.

Check size (depth and width) was dependent on soil-moisture regime, *YA* status, and spiral grain (Table 2. Model: generalized linear mixed model). COND and MARG effects were within 2% of each other. Trees on drier sites had significantly wider and deeper checks ($P < 0.01$) than trees on either mesic or wet sites (Table 2). Mean width of checks on the drier sites was 3.6 mm (±1.6), but only 2.8 mm on the wetter sites (±1.1 mm). Depth of checks averaged 5.3 cm (± 1.7 cm) on the drier sites compared to 4.7 cm (±1.4 cm) on the wetter sites. A very strong effect of site moisture regime was noted in the length of checks in the first 2.5 m of the stem ($P < 0.01$). With an average length of 38 cm (±60 cm), the checks on a dry site were almost four times longer than on wetter sites (mean: 10.2 cm ± 26 cm).

Check depth in *YA* > 2 trees was, on average, about 5.1 cm (± 1.6 cm) or almost 1 cm deeper than in *YA* ≤ 2 trees ($P < 0.001$). Average width of checks for *YA* > 2 was 0.3 cm (± 0.1) or about 50% above the average width of 0.2 cm (±0.1) for *YA* ≤ 2 ($P < 0.001$). The within-tree standard deviation of check size increased with *YA* (Table 2). For depth the rate of increase was 0.17 cm (± 0.03) per year and for width it was 0.016 cm (± 0.002) per year. As checks become deeper they also widen (correlation coefficient of 0.76).

Temporal trends in the relative depth of checks, the proportion of stem basal area impacted by checks, and the proportion of the log volume loss affected by checks are shown in Fig. 2 for trees with and without spiral grain. All differences between the two classes of trees were significant ($P < 0.001$) with spiral-grained trees more adversely affected. Only MARG results are given, COND results were very similar. The average relative depth of checks increased from about 5% (±6%) in *YA* = 1 to about 17% (±10%) at *YA* ≥ 5) and it was about twice as high in trees with spiral grain compared to trees with no spiral grain. The relative depth for *YA* ≤ 2 was significantly lower than for *YA* ≥ 3 ($P < 0.001$).

Temporal changes in the proportion of under-bark *BA* affected by checking were similar to those reported for check depth, except that they were about three times higher. Log-sized volume impacted by checks was similar to those for *BA* except for an unusually high proportion of 74% (±19%) in *YA* = 2 trees with spiral grain.

Stem wood *MC* declined nearly linearly with relative tree height (*RHT, RHT* at top of tree ≡1). The final model for the *k*th disc (*k* = 2,3…,15) in the *j*th tree on the *i*th site was

$$[2] \quad MC_{ijk} = \mu + \sum_{SMR} \beta_{SMR} \times \delta_{SMR} + \sum_{YA=0}^{4} \alpha_{YA} + \beta_{spiral} \times \delta_{spiral} + \left(\beta_{RHT} + \beta_i\right) \times RHT_{ijk} + \varepsilon_i + \varepsilon_{ij} + \varepsilon_{ijk}$$

where notation is as per Eq. [1], β_1 and ϵ_1 are random site-specific intercept and slope modifiers in the regression of *MC* on *RHT*, ϵ_{1j} is a random tree (within site) effect, and ϵ_{1jk} is a residual error. Restricted maximum likelihood estimates of the model parameters are listed in Table 5 for heartwood, sapwood, and combined. Both sites and trees accounted for a significant amount of the variation in *MC*. Wood in trees with spiral grain were, on average, 1% drier ($P < 0.001$) than wood in trees with no spiral grain. *MC* of sapwood dropped by an average of 0.1% (± 0.02%) for every check; about twice the rate determined for heartwood.

MC in dead standing trees declined, as expected, with time since beetle attack. In *YA* = 1 the moisture content was close to 25% (± 6%) which is below the fibre saturation point (Chow and Obermajer 2007). *MC* declined by approximately 1.5% per year (± 0.1%) between *YA* = 1 and *YA* = 4, but the

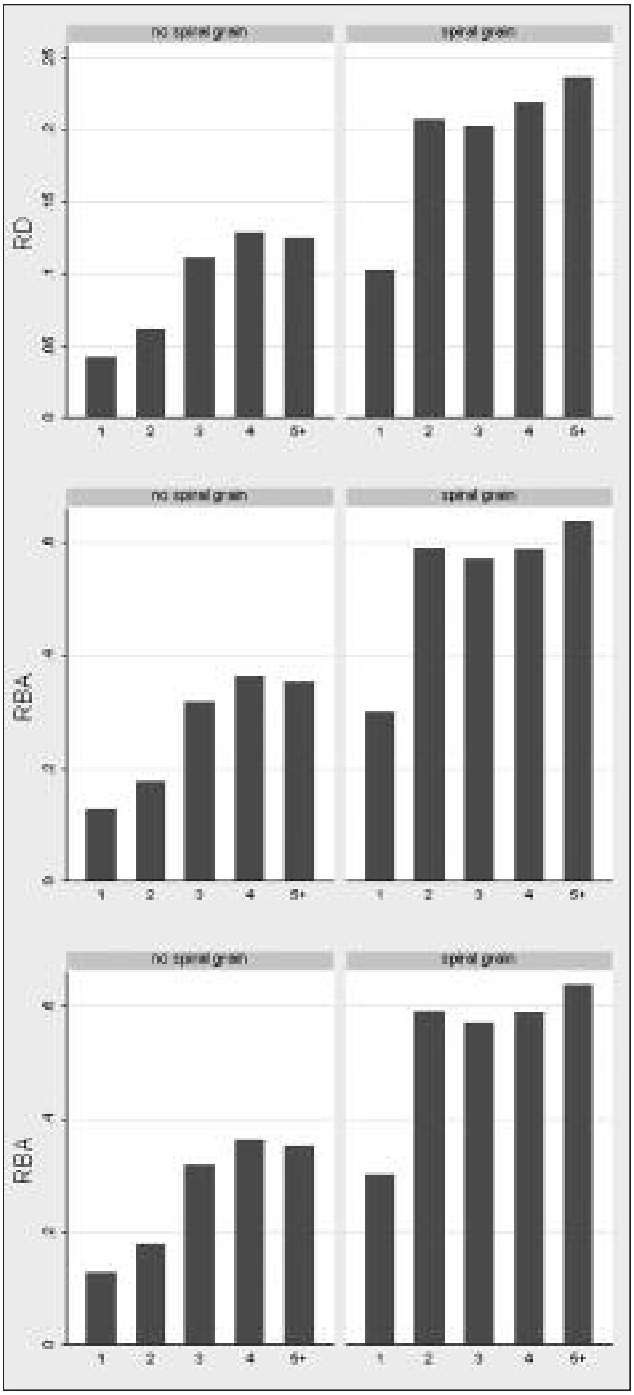

Fig. 2. Relative check depth (RD), relative BA affected by checks (RBA), and relative log volume affected by checks (RVOL) by years since death (1, 2, 3, 4, 5+). All results are volume-weighted averages of stem disc recordings.

decline was steeper between *YA* = 2 and *YA* = 3 than between *YA* = 2 and *YA* = 1 (Table 3) and overall slightly faster in the sapwood (2.1% ± 0.1 %) than in the heartwood (2.0% ± 0.1%).

MC on the dry sites was, on average, 2.4% (±1.1%) lower ($P = 0.03$) than on wetter sites, but no *SMR* effect was significant for heartwood or when the two wood types were combined ($P > 0.21$).

Table 3. Effect sizes of spiral grain, number of checks, YA and relative height (*RHT*) on wood moisture content (*MC%*) in sapwood (*sap*), heartwood (*heartw*) and combined (*wood*). See Eq. [2] for details. *sd* = standard deviation (of random effects). Numbers in parentheses are the estimated standard error of an estimate. Sites are treated as random effects and trees within sites as correlated random variables.

	MC_{sap}	$MC_{heartw^{\cdot}}$	MC_{wood}
Mean	27.3 (0.8)	26.3 (0.9)	27.0 (0.8)
Spiral grain	-1.0 (0.4)	-0.8 (0.4)	-0.9 (0.4)
$n_{check} \times \text{Tree}^{-1}$	-0.1 (0.0)	-0.0 (0.0)	-0.0 (0.0)
Dry	-2.4 (1.1)	-0.6 (1.3)	-1.4 (1.1)
YA=1	3.9 (0.7)	3.3 (0.7)	3.1 (0.6)
YA=2	3.4 (0.6)	3.7 (0.6)	3.3 (0.6)
YA=3	1.9 (0.5)	2.1 (0.5)	1.9 (0.5)
YA=4	0.0 (0.6)	0.0 (0.6)	0.0 (0.5)
YA=5+	0.0 (0.6)	0.0 (0.5)	0.0 (0.5)
RHT	-17.7 (0.7)	-14.9 (0.8)	-16.8 (0.6)
$\widehat{sd}(RHT \times \text{site})$	4.0 (0.6)	4.8 (0.6)	3.5 (0.5)
$\widehat{sd}(Site)$	2.6 (0.4)	3.1 (0.4)	2.6 (0.3)
$\widehat{sd}(Tree)$	1.9 (0.2)	2.4 (0.1)	2.2 (1.2)
$\widehat{sd}(Error)$	6.1 (0.1)	3.2 (0.0)	4.7 (0.1)

A total of 101 trees (28%) had some form of rot or decay in one or more stem section. The rot and decay was concentrated in just 6% of the examined discs and almost exclusively around the center of a disc. Sap rot was the dominant type of rot/decay with 127 cases, followed by insipient rot (79) and *Phellinus pini* (78). About 90% of the incidence of rot/decay was found in the first 2.5 m of the stem.

Rot and decay incidence increased with *YA* but most rapidly between *YA* = 2 and *YA* = 3 and between *YA* = 3 and *YA* = 4 (Table 4) where the changes were highly significantly different from zero ($P < 0.001$). With *YA* = 1 taken as the baseline of rot/decay odds, the COND odds of a rot/decay incidence was 1.1 (±0.8, $P = 0.87$) in *YA* = 2, 3.5 (± 2.4, $P = 0.06$) in *YA* = 3, 8.0 (± 6.3, $P < 0.01$) in *YA* = 4, and 13.7 (± 9.7, $P < 0.001$) in *YA* ≥ 5. Corresponding MARG odds were 1.07 (± 0.7, $P = 0.9$), 3.1 (± 1.8, $P = 0.06$), 4.9 (± 3.1, $P = 0.01$), and 7.4 (± 4.3, $P < 0.001$). Site variation accounted for 40% of the total variation in incidence.

The rot/decay incidence rate in trees with spiral grain was 0.48 (±0.50) as opposed to only 0.20 (±0.40) in trees with no spiral grain (Table 4). Site variation accounted for 40% of the

Table 4. Incidence rate and extent of tree-level rot/decay by years since death (YA), spiral grain, area, and soil moisture regime. Extent is in percent of whole tree volume-weighted stem basal area. Numbers in parentheses are among tree standard deviations.

	Incidence	Extent %
YA=1	0.10 (0.31)	0.6 (1.9)
YA=2	0.14 (0.35)	1.2 (5.6)
YA=3	0.28 (0.45)	2.6 (7.7)
YA=4	0.30 (0.46)	1.9 (6.4)
YA=5 +	0.43 (0.50)	2.0 (5.0)
No spiral grain	0.20 (0.40)	1.7 (0.1)
Spiral Grain	0.48 (0.50)	1.9 (0.1)
Burns Lake	0.38 (0.49)	1.3 (4.6)
Quesnel	0.23 (0.42)	1.2 (3.7)
Vanderhoof	0.22 (0.41)	2.2 (4.1)
Dry	0.46 (0.50)	3.0 (7.0)
Mesic	0.22 (0.41)	1.3 (5.2)
Wet	0.18 (0.38)	1.1 (4.5)

total variation. The odds that a tree with spiral grain has some rot/decay were higher than for trees with no spiral grain (MARG: 3.4 ± 1.3, $P < 0.001$, COND 2.9 ± 0.8, $P < 0.001$).

The incidence rate of rot/decay was significantly higher in Burns Lake (38%) than in Quesnel (23%) and Vanderhoof (22%) (Table 4). With Vanderhoof as baseline (odds = 1), then the odds of some rot/decay in Burns Lake were 4.7 (± 3.3, $P = 0.03$) for COND and 2.9 (± 1.5, $P = 0.03$) for MARG. Corresponding odds for Quesnel were 1.2 (± 1.2, $P = 0.57$) and 1.1 (± 0.6, $P = 0.81$).

Dry sites had significantly higher incidence rates than mesic and wet sites (Table 4). With wet sites as the baseline (odds = 1) the COND odds of some rot/decay on dry and mesic sites were 6.0 (± 4.1, $P = 0.007$) and 1.2 (± 0.8, $P = 0.74$), respectively. Corresponding MARG odds were 3.8 (±1.8, $P = 0.005$), and 1.2 (± 0.6, $P = 0.61$).

The average extent of rot and decay was 1.7% (±5.7%) of the volume-weighted basal area. The maximum disc specific extent was 8.0% ±18.4%. Means and standard deviations for *YA*, spiral grain, area, and *SMR* effects are in Table 4. *YA* had a significant impact on the extent of rot/decay, but only the contrast between $YA \leq 2$ and $YA \geq 3$ was significant ($P < 0.01$). Trees with spiral grain had slightly more rot/decay than trees with no spiral grain (Table 4).

Table 5. Per tree average of blue-stain relative width and relative basal area. Numbers are in percent of volume-weighted stem averages. Weights (wt) are total volume (TVOL) or log volume (LVOL) with a minimum diameter of 12.5 cm. Numbers in parentheses are the among-tree standard deviation across all sites.

YA	**Width%** (*wt* = *TVOL*)	**Width%** (*wt* = *LVOL*)	***BA%*** (*wt* = *TVOL*)	***BA%*** (*wt* = *LVOL*)
1	30 (11)	30 (11)	39 (12)	39 (12)
2	29 (10)	29 (11)	37 (11)	38 (12)
3	26 (7)	25 (7)	32 (8)	32 (8)
4	26 (7)	26 (7)	33 (8)	33 (9)
5+	26 (9)	27 (9)	31 (10)	31 (10)

All trees had some blue-stain (minimum 4% of volume-weighted basal area). A solid stain pattern was the dominant stain type (82%). There was a weak but non-significant trend for the relative extent of blue-stain to first increase and then decrease along the stem axis. The highest average of the relative width and extent of blue-stain was found in $YA = 1$ trees (Table 5) and the lowest in trees with $YA \geq 5$. The fading of blue-stain with time after death may have contributed to this apparent decline. The number of checks per tree had a small positive ($P < 0.01$) effect on the extent of blue-stain of about 0.2% per check (COND and MARG). Otherwise only $YA =1$ was significant in the MARG effect estimates (4.6% ± 2.2%) and differences between COND and MARG estimates were unimportant (< 10%). Sites accounted for approximately 40% of the total variance in extent of blue-stain and almost 70% of the variation in relative width of blue-stain.

Discussion

Findings of this study confirmed general expectations of a fairly rapid decline in important wood quality attributes of dead standing beetle-killed trees (Byrne *et al.* 2005a, Woo *et al.* 2005, Trent *et al.* 2006, Chow and Obermajer 2007).

Checking in standing straight-grained beetle-killed lodgepole pines is considered the most important factor determining the volume recovery and value of sawn lumber (Orbay L. and Goudie 2006, Lewis et al. 2006). Three to five years after being killed by the beetle virtually all standing dead lodgepole pines will have numerous and large (> 2 cm) checks in every 2.5 m stem section (Harrison 2006). Trees with checks are more prone to secondary damage by insect-feeding and cavity-nesting birds. In this study the number of checks per tree was a good indicator of the extent of secondary damage by birds (not shown).

In a review of the literature, Lewis and Hartley (2005) cite studies in which the volume recovery from older (straight-grained) dead logs was around two-thirds of the volume recovered from live logs. Chippable volume, of course, showed the inverse relationship. Other studies have indicated volume recovery losses of 4% one year after death, 8% after three to six years, and 14% for older dead trees. It is, however, difficult to compare our field results to actual milling studies (Orbay and Goudie 2006, Brdicko 2007) as the volume recovery and grade mix depends on the raw material, milling technology, and market conditions (Lewis *et al.* 2006).

This study confirmed spiral grain as an important determinant for the extent and severity of checking (Young and Hamer 1994, Backstrom 2006, Bowyer *et al.* 2007). With a large variation in stand-level proportions of trees with spiral grain it is difficult to predict the severity of checking from *YA* alone. As illustrated by our results, the checking will be most severe on drier sites due to a faster drying rate of the wood (Lewis *et al.* 2006, Trent *et al.* 2006). The large increase in the number and size of checks in the second and third year after death in straight-grained stems suggests a fairly narrow operational window for avoiding a substantial increase in loss of lumber volume and value. According to our results, these losses will be considerably higher on drier sites. It is interesting to note that a report by the BC Ministry of Forests and Range (Eng *et al.* 2007) suggested that wetter sites would show more severe checking. Our results could not support this expectation.

During the first year after a beetle-kill the moisture content of both sapwood and heartwood of dead trees drops to about fibre saturation point (Woo *et al.* 2005, Lewis *et al.* 2006, Trent *et al.* 2006, Chow and Obermajer 2007). After reaching that point the moisture loss continues at rates of 1% to 5% depending on the climate and site condition (Byrne *et al.* 2005a, Lewis and Hartley 2005, Harrison 2006, Lewis *et al.* 2006, Trent *et al.* 2006). Our results generally confirmed these observations and also determined that trees with more checks will dry faster than trees with fewer checks. Since dry wood is more prone to breakage during handling than green wood and is also more difficult to process (Orbay and Goudie 2006), the profitability of processing dead wood is likely to be negatively influenced by a declining moisture content. Tree size did not influence wood moisture content.

It is generally expected that rot and decay in standing beetle-killed trees would be more abundant on wetter sites (Lewis and Hartley 2005, Lewis *et al.* 2006, Eng *et al.* 2007) and that the incidence rates and extent of rot and decay would remain fairly constant during the first four to five years following death (Byrne *et al.* 2005a, Lewis and Hartley 2005). The marked increase in rot incidence (approximately fourfold over 5+ years) found in this study points towards an aggressive invasion of rot-causing fungi possibly peaking two years after death. Invasions that are facilitated by checks, blue-stain, and drying processes (Byrne *et al.* 2005a, Kim *et al.* 2005, Lewis *et al.* 2006). Tree size was not a significant determinant of rot/decay. We surmise that increased (moisture) stress on the drier site has favoured establishment of rot-causing fungi. Our results regarding the extent of rot/decay were better aligned with general expectations.

Blue-stain in wood from beetle-killed lodgepole pines may exclude uses for which appearance is important (Byrne and Uzunovic 2005). Otherwise, blue-stained wood ought to qualify for virtually the same product mix as non-stained wood (Byrne *et al.* 2005a, b; Zaturecky and Chiu 2005; Lum *et al.* 2006; Trent *et al.* 2006). Our results confirmed that all beetle-killed trees have blue-stain (Byrne *et al.* 2005a). One year after the beetle has killed a tree one should expect most of the sapwood to show blue-stain. Again, tree size was not a significant factor for the relative extent of blue stain. Our reported drop in the extent of visible blue-stain over time is ascribed to an oxidation of the stain (Byrne *et al.* 2005a, b; Kim *et al.* 2005). In a laboratory study Chow and Obermajer (2007) found an increase in blue-stain (by volume) during the first three years after death, suggesting that blue-staining fungi continues to invade the wood (Kim *et al.* 2005).

The sheer magnitude of beetle-attacked wood volume available for harvest in British Columbia makes immediate harvesting of the bulk of all beetle-killed trees with subsequent storage under sprinklers (Feng and Knudson 2005) until processed at a mill an unlikely scenario. As pointed out the economics of storing large volumes of wood in water are not compelling in today's marketplace (R&S Rogers Consulting Inc. 2001). For the time-being beetle-killed trees can economically be stored only as standing dead. The results from this study will help provincial and industrial planners quantify opportunity costs in their scheduling harvest operations of standing dead beetle-killed lodgepole pines in British Columbia. The extensive and balanced sampling of a broad spectrum of stand conditions makes this study valuable as it quantified a considerable among-stand variation in all important examined wood quality traits. That variation points to the need of stand-level information to further this planning.

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