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Fire damage effects on red oak timber product value

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ABSTRACT

Land managers use prescribed fire for a variety of resource objectives on sites containing merchantable trees. We analyzed how fire-caused injuries (i.e., fire scars) affect lumber volume and value in 88 red oak (*Quercus velutina, Quercus rubra, and Quercus coccinea*) butt logs from trees harvested from three sites in southern Missouri. Trees with varying amounts of external fire damage, time since fire, and diameter were harvested and milled into dimensional lumber. We tracked lumber grade changes and volume losses due to fire-related injuries on individual boards ($n = 1298$, 18.3 cubic meters (7754 board feet)). Most analyses considered value loss to the individual butt log. We identified threshold values for fire-scar height and percent basal circumference injured, beyond which value loss is expected. Our analysis produced two models to describe how butt log value loss relates to fire-scar dimensions and residence time (timespan between damage occurrence and tree harvest). Overall, value and volume losses due to fire damage were low. If fire damage is less than 50 cm in height and 20% of basal circumference, our study suggests little value loss is to be expected within 14 years of injury. If these thresholds are exceeded, value loss is likely, and increases over time. Value loss is very low if trees are harvested within approximately five years after fire damage, regardless of scar size. These findings are applicable for red oak trees which are at least 20 cm diameter at breast height at time of fire damage and with fire-scar residence times not greater than fourteen years.

1. Introduction

Prescribed fire use has recently increased in both occurrence and acceptance (Dey and Hartman, 2005; Nowacki and Abrams, 2008) in oak (*Quercus*) forests of the eastern United States. It is employed as a tool for natural community restoration, hazardous fuels reduction, and silvicultural objectives (Agee, 1996; Pyne et al., 1996; Brose and Van Lear, 1998; Hartman, 2005; Nowacki and Abrams, 2008; Burton et al., 2011; Arthur et al., 2012; Brose et al., 2013). Many studies have documented the ability of oak trees to survive different fire severity conditions with varying degrees of damage (Loomis, 1973; Abrams, 1992; Hengst and Dawson, 1994; Regerbrugge and Smith, 1994; Brose and Van Lear, 1999). Public land management agencies are commonly tasked with managing forestlands for multiple objectives. Among land managers in much of the deciduous forests of eastern North America, prescribed fire and timber production are perceived as conflicting practices (Ryan et al., 2013). More research is needed to understand how fire affects timber product values. Here we quantify the economic cost of applying prescribed fire in forest stands containing oak trees of merchantable size for typical dimensional lumber products.

Heating of cambial tissue leads to the scarring of tree boles, and thus provides an entry point for wood-degrading fungi and insects (Nelson et al., 1933; Berry and Beaton, 1972; Shigo, 1984; Gutsell and Johnson, 1996; Brose and Van Lear, 1999; Bova and Dickinson, 2005). Modern studies in oak ecosystems have investigated fire-scar characteristics (Smith and Sutherland, 1999), landscape and fire-intensity influences on fire scarring (Regerbrugge and Smith, 1994; Stevenson, 2007), fire-scar formation likelihood (McEwan et al., 2007), and relationships among fire-scar formation, tree diameter, and growth rate (Guyette and Stambaugh, 2004).

Very few studies have investigated timber product value losses on fire-damaged trees. Burns (1955) estimated scalable defect and cull on fire-damaged red oaks in southern Missouri. He found that much of the cull was associated with fire damage (compared to insect and branching defects), and that 70% of lumber value loss was due to volume loss and 30% due to quality loss (log grade change). Loomis (1974) scaled and graded (Ostrander, 1965) fire-damaged oak sawlogs to assess fire-related defects. Fire-scar measurements and tree characteristics (diameter and age) were used to predict lumber value and volume loss. This analysis showed that wound length, followed by wound age, were the

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strongest predictor variables. Guyette et al. (2008) investigated prescribed fire effects on volume and log grade on three oak species (*Quercus coccinea, Quercus velutina,* and *Quercus alba*) in southern Missouri. They reported that log grades changed very little and the volume of decayed wood was low 6 years after fire damage.

Previous research has emphasized the fire-damaged area, but ignored the portions of the log not affected directly by the fire wound. Nor have these studies discounted fire damage that does not affect lumber values because it lies outside the scaling cylinder, and is removed during the milling process. Also, studies have not considered that dimensional lumber of all grades allow for a range in levels of defect (NHLA, 2010), and that only when defect thresholds are surpassed does lumber grade decrease, resulting in value loss.

Rather than focusing solely on the fire-damaged area, we assessed the fire-caused value loss through analysis of the dimensional lumber sawn from fire-damaged butt logs. We measured value loss in terms of dimensional lumber products milled from fire-damaged red oak (genus *Quercus* section *Erythrobalanus*) trees in southern Missouri. We compared the expected (as if no fire damage occurred) and observed values of dimensional lumber products (boards and cants) sawn per butt log to determine the value loss of individual butt logs to fire damage. Dimensional lumber is an ideal unit for this evaluation because multiple grades are recognized within the hardwood industry for red oak lumber, thus allowing for fine-scale valuation (NHLA, 2010). This valuation allowed for the detection of losses due to lumber grade changes, rather than only volume. In this study, we determined if fire-scar extent, tree size (diameter breast height (DBH) measured at 1.37 m above ground), and fire-scar residence time effectively predict value loss in the butt log.

2. Methods

2.1. Study sites

Ninety trees were harvested from prescribed burned units and areas of known wildfires at three Conservation Areas (CA) managed by the Missouri Department of Conservation (MDC) in southern Missouri: Peck Ranch (Carter Co.), Lead Mine (Dallas Co.), and Graves Mountain (Wayne Co.). Stand overstories were comprised of even-aged cohorts of oak and hickory (*Carya*) trees, with sparse mid- and under-stories due to repeated prescribed fires. Trees species selected for harvest included black oak (*Q. velutina* Lam.), northern red oak (*Q. rubra* L.), and scarlet oak (*Q. coccinea* Muenchh.). Dimensional lumber products from these species are considered interchangeable (Hardwood Market Report, 2011).

Prescribed fire was used at all sites to restore and manage woodland natural communities (Nelson, 2005). Peck Ranch and Graves Mountain had been prescribed burned 4 times over a 14 year period. Prescribed fire was applied three times at Lead Mine over 10 years. Management objectives for using prescribed fire at these sites included top-killing understory woody stems, stimulation of native ground flora, and leaf litter depth reduction. Merchantable-sized trees (i.e., DBH > 20 cm) were harvested from areas adjacent to glades at Lead Mine and Graves Mountain and woodlands at Peck Ranch. All trees were harvested from MDC "Site Class 2" sites (MDC Staff personal communication May 2012), that have a black oak site index of 17–20 m (55–64 feet) (McQuilkin, 1974). Time between prescribed fire events and harvest of sample trees (fire-scar residence time) ranged from 1 to 14 years.

2.2. Field sampling

Trees of varying merchantable size, log grade (Rast et al., 1973), time since fire, and severity of fire-caused injury (fire scar) were purposely selected for sampling. To be considered for sampling, trees were required to be at least 20 cm (9 in.) DBH, and have evidence of fire damage (i.e., tree tissue growth initiated by fire-caused local cambial death). The tree selection process sought to include a diverse combination of fire-scar and tree sizes. We identified external fire scars by their triangular shape typically on the uphill side at the base of trees, and presence on adjacent trees in the immediate area (Paulsell, 1957; Gutsell and Johnson, 1996; Guyette and Cutter, 1991; Smith and Sutherland, 1999; Guyette and Stambaugh, 2004). Tree DBH and external fire-injury dimensions (scar height (ScarH), scar width (ScarW), and scar depth (ScarD)) for each tree were measured in the field (Fig. 1). ScarH was measured from the base of the leaf litter to the top of the damaged area; ScarW at the widest point; and ScarD at the deepest point within the fire-scar area. ScarD was measured as the distance from the dead cambial tissue to the outside edge of the encroaching new growth, i.e., 'woundwood ribs', defined as the new growth covering the dead cambium caused by the thickened annual growth rings (Smith and Sutherland, 1999). The fire-damaged area was defined as the area of new cambial growth (including smooth newly formed bark) immediately surrounding the exposed killed cambium. In the case of closed fire scars (i.e., already healed over fire scars), depth was not measurable and was recorded as 0.3 cm (0.1 in.). All other scar types had exposed dead cambium visible surrounded by encroaching new growth.

Professional loggers were contracted to harvest and deliver the butt logs to a local mill. Each tree was cut as low as possible to the ground to retain the fullest extent of fire damage. The butt log was cut to a 2.6 ($n = 14$) or 3.2 ($n = 76$) meter length (8.5 or 10.5 feet). The base of each butt log was painted a unique color combination to facilitate log and board tracking through the milling and grading process. A basal cross-section was retained from the top of each stump for fire-scar analysis.

2.3. Laboratory

Basal cross-sections were sanded with progressively finer sand paper (80–600 grit) to reveal cellular detail of annual rings and fire-scar injuries. Fire scars on cross-sections were identified by the presence of callus tissue, cambial injury, and woundwood ribs that covered the dead cambium (Smith and Sutherland, 1999). Fire injury years and tree ages were identified using standard dendrochronological methods (Stokes and Smiley, 1968). Fire-scar years were reported as the first year showing growth response to the fire injury. Measurements made on each basal cross-section included: radius at time of each fire injury and at time of harvest (pith to year of injury or outside bark), and the length injured along

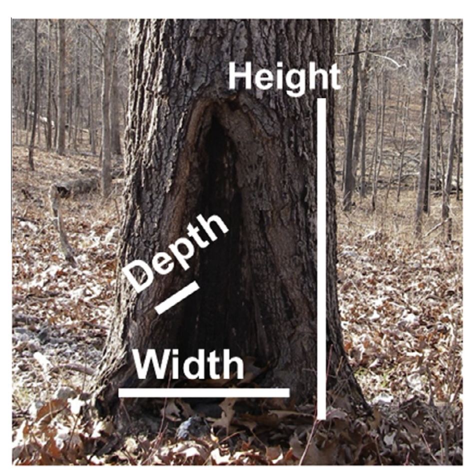

Fig. 1. External scar measurements measured in the field.

Fig. 2. Fire-scar measurements made on basal cross-sections retained from the top of the stump of all sampled trees. Line A is the radius at time of harvest; Line B is the radius at time of injury; and Line C is the length of the basal circumference injured. Values for A and B lines were the average of two measurements.

the circumference of the cross-section for each fire scar (scar arc) (Fig. 2). To account for the non-circular shape of the cross-sections, we calculated radius measurements by averaging two perpendicular measurements. Fire-scar years were compared to MDC fire records and classified as either 'prescribed' or 'wildfire'.

2.4. Milling and grading

We used standard hardwood log grading methods (Rast et al., 1973) to evaluate and assign factory-lumber log grades to each log. Grades were assigned ignoring the fire-caused defect to describe log quality as if no fire damage had occurred. To ensure that the log was milled consistently with the assigned log grade (which ignored fire scarring), a white line was painted on the log indicating the worst face. A professional mill operator sawed the logs on a portable band-saw mill with a measured kerf of 0.2 cm (0.09 in.). Milling instructions were to first remove the worst face (due to non-fire defects), and then to mill each log for the largest amount of the highest grade 2.9 cm (1.125 in.) dimensional lumber possible, ignoring the fire-caused defect. Logs were milled down to a 10.2 cm (4 in.) square post (cant) which contained the pith. Lumber was cut to variable widths and wane was removed with an edger.

Each board was assigned a sample number indicating the tree and board number. All defects (discoloration, rot, char, missing wood) associated with fire injuries were marked on each board and cant with a wax marker. An observer was located adjacent to where the band-saw blade cut into the log to view the fire-damaged area as it was sawn, thus identifying which defects in the lumber were spatially related to the external fire damage. This allowed for differentiation between areas of fire damage and lumber defects due to other causes (e.g., insect damage, branch knots, decay related to broken limbs).

A National Hardwood Lumber Association (NHLA) trained lumber grader assigned volume and lumber grade to each board according to NHLA grading rules (NHLA, 2010). Cants were evaluated in terms of volume, either sound or cull. To determine actual and expected board volume and grade, all boards with fire-related defects were graded and scaled twice:

(1) as observed, deducting for fire-related defects;
(2) as if fire-related defect was not present.

The NHLA recognizes six different red oak lumber grades (in decreasing value): First and Seconds (FAS), Select and One Face (Select/1Face), 1 Common, 2 Common, 3A, and 3B (NHLA, 2010). Lumber grade is dependent on board width, length, and the size, position, and number of clear and sound cuttings. Clear cuttings refer to the amount of surface area of a board that is clear of defect (e.g., rot, branch knots, insect damage), usually determined on the worst side of the board. Sound cuttings refer to the surface area of a board that, though it may contain aesthetic defects, the structural integrity of the board is not compromised (NHLA, 2010). Different amounts of defect are tolerated per grade. Volume was determined based on NHLA lumber scaling guidelines (NHLA, 2010).

3. Analysis

3.1. Measurements

Two logs were removed from the data set prior to analysis because extensive rot made it difficult to discern fire from non-fire related defect and to determine date of fire-scar occurrence. This left a total of 88 trees from which 1298 dimensional lumber products (18.3 m^3 (7755 board feet total volume)) were produced, subsequently referred to as the *entire data set*. We used the Hardwood Market Report Southern Hardwoods Category (April 16, 2011) to assign lumber values (Table 1) to each board. Because the Hardwood Market Report does not give values for the lowest lumber grade (3B) recognized by NHLA, the local price for rough, green 3B grade lumber (personal communication, Master's Craft Flooring Company, West Plains, Missouri, April 2012) was used. The Hardwood Market Report also does not list different grades of cants, therefore the value loss of cants was determined by volume loss due to fire damage. All values were for rough green lumber, not stumpage. Expected and actual board and cant values and volumes were summed for each butt log.

We calculated the following variables for each butt log:

Expected log value (ELV)	the value expected if no fire damage occurred
Actual log value (ALV)	the actual value including fire damage defects
Expected log scale (ELS)	the volume of lumber that would have been generated by each log if the fire damage not occurred
Actual log scale (ALS)	the observed volume of lumber including fire-caused volume loss

$$\text{Percent value loss (PVL)} : (1 - (ALV/ELV)) * 100 \quad (1)$$

$$\text{Percent scale loss (PSL)} : (1 - (ALS/ELS)) * 100 \quad (2)$$

Tree DBH was transformed to tree basal area (TBA) using the geometric formula for the area of a circle. Fire-scar residence time (R-time) was calculated by subtracting the calendar year of fire injury from the year of harvest for all fire scars. Percent basal

Table 1
Lumber values for dimensional lumber products per 2.36 cubic meters (one thousand board feet) for rough green lumber (Hardwood Market Report, April 16, 2011).

FAS	1 Face/Select	1 Common	2 Common	3A	CANT	3B	Cull
$880	$870	$560	$450	$375	$330	$82.50[a]	$0

[a] Personal communication (April 2012), Master's Craft Flooring Company lumber distributer (West Plains, MO.).

circumference injured (ScarArc%) was calculated for all fire scars by dividing the scar-arc length by the basal circumference, which was derived from the basal radius at the time of fire injury (basal circumference = basal diameter $* \pi$). To estimate DBH at time of fire injury (DBH_i) a taper equation was calculated for each tree by dividing DBH at time of harvest (DBH_h) by the basal cross-section diameter. This taper equation was then multiplied by the basal diameter at time of injury. Summary statistics (mean, range, and standard deviation) were calculated for all external fire-scar measurements, tree ages, DBH, PVL, and PSL. For all statistical summaries and analyses, we used The R statistical computing package (2008).

3.2. PVL model-External fire-scar and tree measurements

We hypothesized that external fire-scar size dimensions (ScarH, ScarW, and ScarD) and tree size (DBH_h) would be significant predictors of individual butt log value loss (PVL). Correlation analysis was used to determine if these were significantly ($p < .05$) correlated with PVL. The data set was stratified to minimize the effect of tree size at time of injury. We excluded trees with fire damage greater than 30 years before harvest (likely small trees at time of injury) from this analysis. Closed fire scars were also excluded due to the inability to measure external fire-scar dimensions. This data set is referred to as the *PVL data set*.

An interactive variable, the Fire Damage Index (FDI), was created by dividing the product of fire-scar dimensions (ScarH and ScarD) by tree basal area (TBA). Ordinary least squares regression was used to describe the relationship between FDI and PVL.

3.3. VLDFS analysis

Most (84 of 90) trees had sustained fire-injuries multiple times; either wildfires, prescribed fires, or both. All logs with fire injuries from multiple years were evaluated for the potential of linking the observed external fire damage and subsequent devaluation (if any) to one particular fire scar per tree. The range of fire-scar complexity sampled is shown in Fig. 3. We compared scar-arc measurements and ScarArc% calculations among individual logs to determine if one fire scar could be identified as the value loss driving fire scar (VLDFS). Many trees had significantly more damage from one fire event than others, therefore, the value loss (if any) could be attributed to one fire. Some trees (i.e., Fig. 3B) experienced fire damage early in life and effectively healed over the injury, but were then injured by fire again later in life. In these trees, no decay was associated with the early fire scar, and value loss was attributed to the subsequent fire scar. Fig. 3C depicts one large fire scar with substantially smaller fire scars from subsequent fires. In this case, value loss was attributed to the large fire scar. Some trees were a combination of 3B and 3C, i.e., they were scarred when small, healed over quickly, but had one or more injuries from prescribed fires that were associated with the observed damage. A VLDFS was not determinable for trees such as that in Fig. 3D where a cross-section records six fire scars throughout the tree's life. The VLDFS was determined for 68 trees, which were then stratified to exclude trees with VLDFS values greater than 30 years and those where external fire damage was healed over. This data set is referred to as the *VLDFS data set*. Separate summary statistics were calculated for significant variables in the *VLDFS data set*. Scatterplots were created to inspect the relationship between PVL, ScarArc% and ScarH.

Fire scars on trees were classified into three groups based on when they occurred in relation to the VLDFS fire scar: Before VLDFS (white dashed line Fig. 3B), VLDFS (black dashed lines Fig. 3A–C), and After VLDFS (white dashed lines Fig. 3C). The average R-time and DBH at time of injury were determined for each of these classifications.

Because the *VLDFS data set* made it possible to attribute a single fire-scar residence time to each tree sampled, we used this dataset to assess fire-scar residence time influence on PVL.

4. Results and discussion

4.1. Summary statistics

The *entire data set* is diverse in terms of tree sizes at harvest, log grades, and degree of fire damage (i.e., fire-scar dimensions). Most

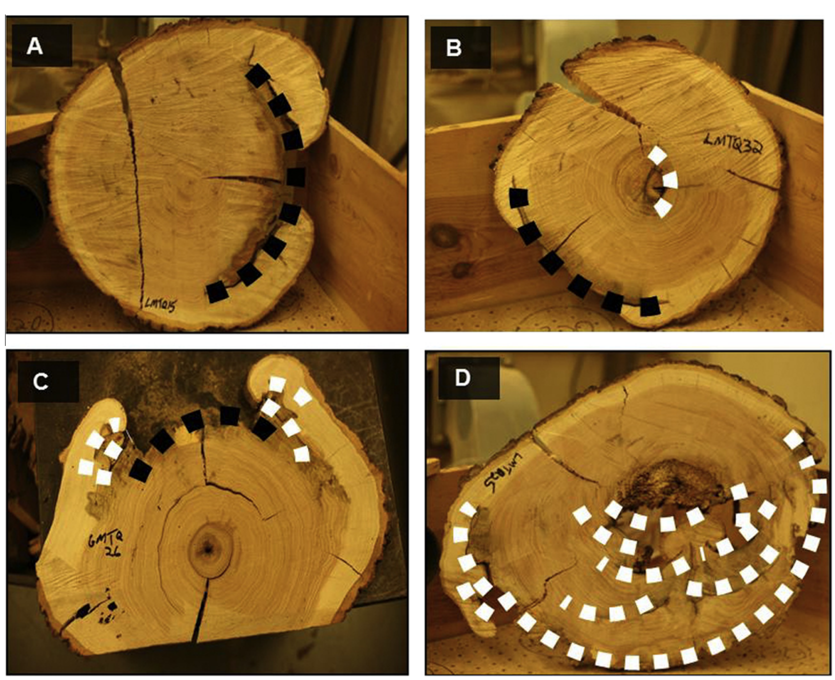

Fig. 3. Examples of individual tree fire histories recorded on basal cross-sections. A single value loss driving fire scar (VLDFS) was determined for trees based on the relative percent circumference injured and considering whether the tree successfully compartmentalized the injury, thus not leading to significant decay. Fire scars are labeled with dotted lines, VLDFS fire scars in black. VLDFS was not determined for 3D because fire-related injuries reoccurred for most of the tree's lifespan.

trees were black oaks ($n = 57$) with lower numbers of northern red ($n = 20$) and scarlet ($n = 11$) oaks. Log grade (ignoring fire defect, Rast et al., 1973) frequency approximated a normal distribution; there were more mid-quality logs (i.e., F2 ($n = 41$)), than high-quality logs (i.e., F1 ($n = 17$)), and low quality logs (i.e., F3 and Local Use (combined $n = 30$)). Tree ages at time of harvest ranged from 43 to 180 years with a mean of 84.2 years. Tree size and fire-scar dimensions for the *entire*, *PVL*, and *VLDFS data sets* are listed in Table 2.

We observed a total of 233 fire scars on 88 trees in the *entire data set*. Percent basal circumference injured (ScarArc%) ranged from 1.2% to 80.7%. All fire scars occurred in the dormant season (in between annual tree-rings), suggesting late-fall to early-spring season of burning. The majority of fire scars analyzed in this study were from prescribed fires, though fire-scars from wildfires also occurred. Prescribed fire-scar residence times ranged from 1 to 14 years. Thirty different wildfire years were recorded on 37 trees with fire-scar residence times ranging from 9 to 153 years. Most of these fire scars were on trees excluded from analysis due to stratifications. Eight of the 122 fire scars in the *PVL data set* were from wildfires, the remaining 114 (93.4%) resulted from prescribed fires; 49 of the 57 VLDFS fire scars were due to prescribed fires (86.0%).

4.2. Volume vs. value loss

Individual tree volume loss (PSL) was considerably less than individual tree value loss (PVL), 3.9% and 10.3% respectively, for the *entire data set*. Fifty-seven of 88 logs had value losses while only 37 experienced volume losses. Considering all of the lumber generated in the *entire data set* pooled together, higher value grades (FAS, 1 Face/Select, 1 Common, and 2 Common) had actual volumes that were lower than the expected volumes; and low value grades (3A, 3B and cull) had actual volumes that were higher than the expected values (Fig. 4). Two-thirds of the boards which lost value did not lose volume. Rather, fire-scar damage was counted as defects in the grading process (identical to insect damage, knots, etc.), reducing the number of clear cuttings per board and causing a shift to a lower lumber grade.

4.3. PVL predictive model

Pearson's correlation (r) analysis identified ScarH and ScarD to be significantly correlated to PVL ($r = 0.52$ and 0.67 respectively, $p < 0.001$). External fire-scar width (ScarW) was not related to PVL ($r = 0.03$, $p = 0.844$). ScarW is likely a poor predictor because woundwood ribs grow faster compared to other parts of the bole (Smith and Sutherland, 1999); consequently, this measurement will vary greatly depending on R-time. Previous studies have also found fire-scar height to be an important predictor of wood quality or volume loss (Loomis, 1974; Loomis and Paananen, 1989; Guyette et al., 2008).

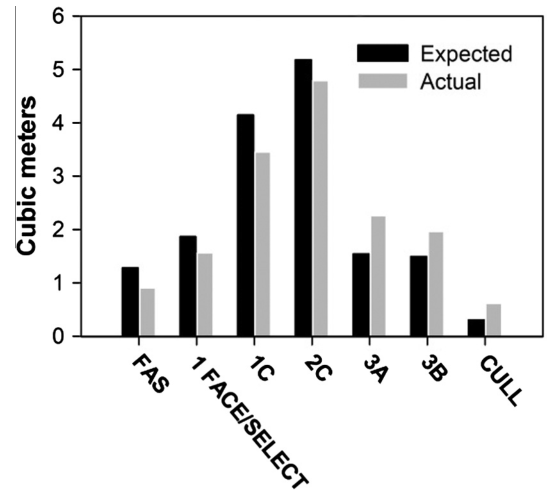

Fig. 4. Expected and actual volume per lumber grade (descending order left to right) for all 1298 dimensional lumber products sawn from the 88 butt logs included in analyses.

A significant linear regression equation was developed predicting PVL with FDI as the independent variable (Fig. 5).

$$PVL = 0.0051 + (13.5 * FDI) \quad r^2 = 0.71, n = 49, p < 0.001 \quad (3)$$

A field reference table (Appendix A) was developed using Eq. (3) to estimate PVL of fire-damaged butt logs.

The PVL model is best suited for use on red oak trees that have an open scar face. Closed scars can result from very recent small injuries that were quickly compartmentalized (i.e., minor wound and associated decay) or from old extensive fire damage that healed over, with extensive rot and decay under the surface. In cases of closed scars, other methods for assessing the degree of

Table 2
Summary statistics for important PVL predictor variables in the *PVL* and *VLDFS data sets*.

	Number of observations	Range	Average	Standard deviation
All trees analyzed				
DBH_h (cm)	88	24.1–62.9	40.9	9.3
PVL (%)	88	0–68.1	10.3	14.1
ScarH (cm)	88	15.2–391.2	86.3	64.5
ScarD (cm)	88	0.3–37.8	6.8	6.1
ScarW (cm)	88	2.5–142.2	49.3	32.4
PVL data set				
DBH_h (cm)	49	25.9–57.9	40.9	8.5
PVL (%)	49	0–68.1	10.1	14.5
ScarH (cm)	49	15.2–391.2	97.0	76.5
ScarD (cm)	49	2.5–26.7	7.6	5.2
ScarW (cm)	49	16.5–142.2	53.3	26.1
VLDFS data set				
DBH_h (cm)	57	25.9–62.2	41.9	9.2
DBH_i (cm)	57	15.8–50.4	33.1	9.8
PVL (%)	57	0–49.5	8.6	11.5
ScarH (cm)	57	17.6–391.2	94.8	73.4
ScarD (cm)	57	2.5–20.3	7.6	4.4
ScarW (cm)	57	16.5–142.2	54.3	29.4
R-time (years)	57	2.0–14.0	9.0	4.0

DBH_h = Diameter at breast height (DBH) at time of harvest; DBH_i = DBH at time of VLDFS injury; PVL = percent value loss to butt log due to fire damage; ScarH = fire-scar height; ScarD = fire-scar depth; R-time = time (years) between fire-damage occurrence and tree harvest.

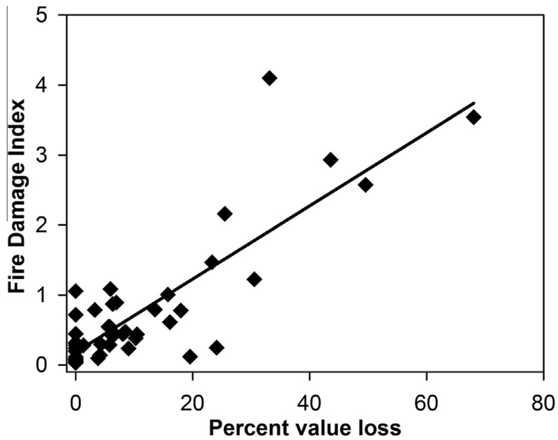

Fig. 5. Scatterplot and regression line (Eq. (3)) of Fire Damage Index (scar height * scar depth)/tree basal area) values and percent value loss.

decay (e.g., sounding bole with a hammer) may be more useful than this model. Fourteen years was the maximum fire-scar residence time well represented in this model, only 3 of 146 fire scars had residence times greater than 14 years.

4.4. Fire-scar size thresholds

The *VLDFS data set* allowed for detection of threshold values and relationships in the data that would not be possible otherwise. A threshold value refers to a maximum value in the independent variable, up to which there is little or no response from the dependent variable, and beyond which there is considerable effect. Threshold values were identified for scar height and ScarArc%, where natural breaks occur in relation to the percent value loss of individual logs (Fig. 6). The great majority (83% and 94% respectively) of trees with any value loss had fire-scar heights greater than 50 cm and ScarArc% greater than 20%. DBH at time of injury (DBH_i) for all VLDFS fire scars was greater than 15.8 cm (Table 2). These thresholds suggest that fire-scar heights less than 50 cm and ScarArc% values less than 20%, on merchantable-size sawlogs, are unlikely to experience any value loss if harvested within 14 years.

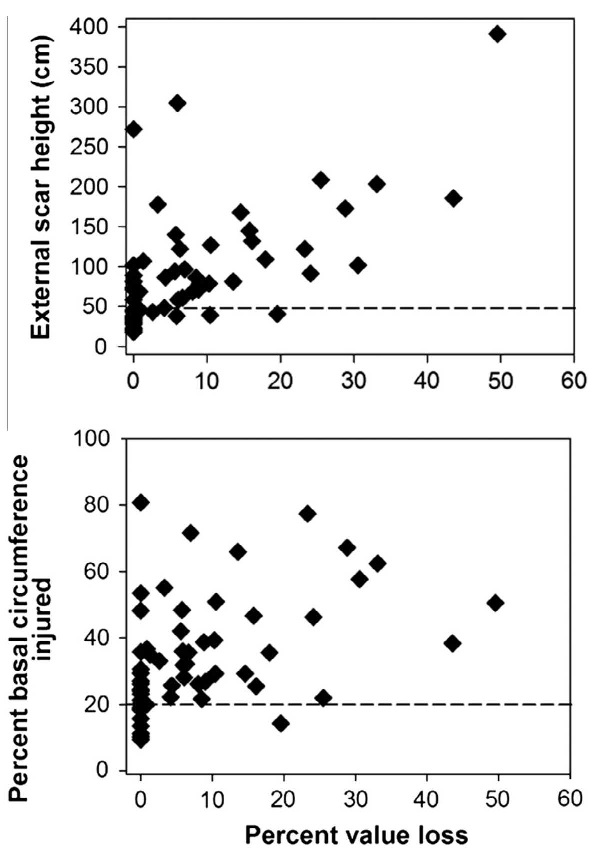

Fig. 6. Scatterplots of percent value loss (PVL) and external scar height (ScarH, top plot) and percent basal circumference injured (ScarArc%). Dotted lines represent suggested thresholds.

All (148) individual fire-scars in the *VLDFS data set* can be classified as either the VLDFS fire scar, or a fire scar that occurred either before or after the VLDFS was formed. Average DBH_i (DBH at time of injury) and R-time for each of these classes are listed in Table 3. Sixty-five fire-scars on 38 trees occurred after the VLDFS (e.g., white dashed line Fig. 3C). The slabs that were removed in the milling process contained these fire scars. The average R-time for these discarded fire scars was 3.8 years, and the average DBH_i was 38.7 cm. The class of fire-scars that occurred before the VLDFS ($n = 27$) were effectively compartmentalized (*sensu* Shigo, 1984) when the tree was relatively small (average DBH at time of fire injury = 17.6 cm, average R-time = 45.5 years). Any associated lumber defect was contained within the square cant (e.g., white dashed line Fig. 3B). DBH_i for injuries that were healed over without resulting in value loss tended to be smaller, and tree size for injuries whose defects were removed in the milling process tended to be larger.

Loomis (1974), Crosby (1977), Guyette et al. (2008) all suggest that there is a time period in a tree's development when fire defects are more likely to lead to value loss. Their results suggest that value loss is limited when injuries on small trees are quickly healed over, as well as when scarring occurs near the time of timber harvest, because the slab material contained the defect. We observed (Table 3) similar results. Trees in the pole size (e.g., ~13–28 cm) class may be more likely to experience higher value loss at time of harvest if allowed to be carried through rotation age, since they necessarily have high fire-scar residence time values. Trees with fire-scar heights greater than 50 cm and basal circumference injuries greater than 20% may be the most vulnerable to experience higher value loss if allowed to remain in the stand through a typical black oak rotation (80–100 years).

4.5. Fire-scar residence time

Two biological activities, tree growth and wood decay, lead to deeper external wounds over time. Loomis (1974), Guyette et al. (2008) found time since fire injury was an important predictor of decay extent. We observed that PVL was strongly influenced by fire-scar height (ScarH) and fire-scar depth (ScarD). Therefore, we used the *VLDFS data set* to predict how PVL is influenced by fire-scar residence time (R-time). Possible relationships were explored between ScarD and R-time, under the supposition that ScarD is a function of tree growth and wood decay, both governed by R-time.

We developed a logarithmic regression model that significantly ($p < 0.05$) predicted ScarD based on R-time (of the VLDFS):

$$\log_{10}(\text{ScarD}) = 0.1238 + 0.0938 * (\text{R-time})$$
$$\text{multiple } r^2 = 0.55, p < 0.001 \quad (4)$$

Table 3
Fire-scar information for *VLDFS data set*.

	Before VLDFS	VLDFS	After VLDFS
Number of fire scars	27	57	65
Avg. DBH_i (cm)	17.6	33.4	38.7
Avg. fire-scar residence time (years)	45.6	8.8	3.8

VLDFS = value loss driving fire scar, single event to which value loss (if any) is attributed.
DBH_i = calculated tree diameter at 1.37 m above ground level, at time of injury.

The exponential model: ScarD = $e^{(0.12383+0.09376*(\text{R-time}))}$was significant in estimating ScarD (an important PVL model variable) based on R-time (Fig. 7).

Linear and exponential models (with and without variables interacting) were subsequently assessed based only on ScarH and R-time. We selected the linear model with interactive variables due to its superior multiple r^2 and better fit to the data, which we visually assessed in scatterplots.

$$\text{PVL} = -4.0595 + (0.6414 * (\text{ScarH})) + (0.1893 * (\text{R-time})) + (0.0060 * (\text{ScarH} * \text{R-time})) \quad \text{multiple } r^2 = 0.51, n = 57, \text{model } p < 0.001 \quad (5)$$

We calculated annual percent value loss for the range of fire-scar heights well represented in the data set (>3 observations). For fire-scar heights between 50 cm and 175 cm, we estimated that annual percent value loss would be 0.49% to 1.25% (Table 4, Fig. 8). It is important to note that ScarD and R-time may not have a linear relationship (Fig. 7), thus this model may not be appropriate beyond 14 years after fire injury. If the fire damage has been present long enough to measure fire-scar depth, Eq. (3) can be applied to determine value loss between fire occurrence and time of measurement, and the annual rate of value loss (Fig. 8) can then be applied to predict the additional value loss at a point in time in the future (within 14 years fire-scar residence time).

We measured the changes in values of a single but important oak product (i.e., dimensional lumber) due to fire damage. Changes in values to other products are likely different depending on multiple factors such as market values and log defects. For example, railroad ties, a common regional product derived from oaks, could undergo different lumber product devaluation given the same tree and fire-scar dimensions. Minor injuries such as small amounts of insect damage or small fire scars likely lead to no devaluation in railroad ties but change grades of lumber. Alternatively, compartmentalized injuries in the center of the tree may preclude a log from producing a tie, but if milled into dimensional lumber, little value loss will be realized.

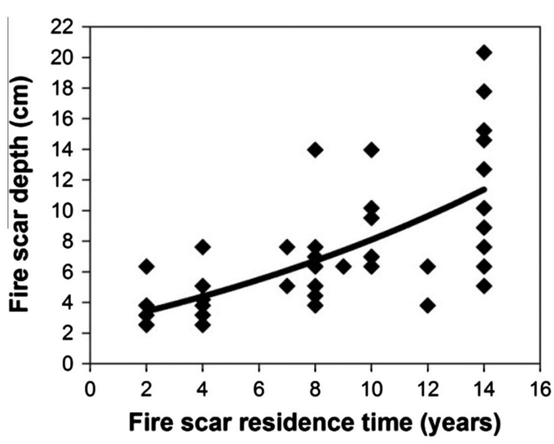

Fig. 7. Scatterplot of fire-scar depth (ScarD) and fire-scar residence time (R-time). Exponential regression line equation: ScarD = $e^{(0.1238+(0.0938*(\text{R-time}))}$; $r^2 = 0.55$, $p < 0.001$.

Table 4
Annual percent value loss of red oak butt logs for different fire-scar heights.

ScarH (cm)	PVL_a (%)
50	0.49
75	0.64
100	0.79
125	0.94
150	1.09
175	1.25

ScarH = fire-scar height.
PVL_a = percent value loss per year of fire-scar residence time.

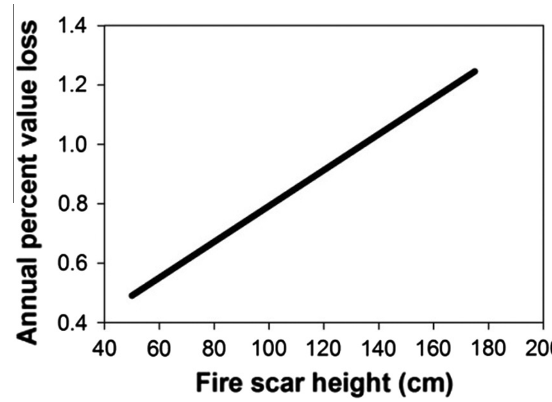

Fig. 8. Line graph depicting change in annual percent value loss caused by increasing fire-scar height.

Previous studies have shown that fires often do not damage oak trees to any extent (Brose and Van Lear, 1999; McEwan et al., 2007). Brose and Van Lear (1999) found that efforts toward minimizing logging slash built up at the base of residual overstory trees in a shelterwood harvest can significantly reduce bole damage due to fire. These efforts include directional felling (to control location of logging slash) and manually disrupting logging slash occurring near residual overstory trees. Therefore, relatively simple efforts may minimize fire-scar size and value loss.

The valuation of prescribed fire effects on the economics of forests and woodlands have many dimensions. This study focused on the devaluation of dimensional lumber products from fire-scarred red oaks, but there are other important components that should be considered when judging prescribed fire effects on the economic value of timber. These include the density of scarred trees, the species scarred, and perhaps of most economic significance (in terms of timber products), changes in forest stand structure and species composition. Future studies should focus on examining fire-damaged trees with fire-scar residence time greater than 14 years, fire effects on other timber products such as staves or veneer, the application of such models to landscapes rather than only individual trees, and quantifying the reduction in timber production capability of a forest stand due to fire-induced changes in structure in and species composition.

5. Conclusion

This study showed that fire-scar size and tree-size measurements can be used to estimate value loss in terms of product values for dimensional red oak lumber. Overall, value and volume losses were low for trees with significant visual fire damage. Certain amounts of damage led to little or no product devaluation. Trees with fire injuries less than 50 cm in height and 20% of circumference (ScarArc%) had nearly no value loss over 14 years after fire injury (R-time). Trees with fire injuries substantially above these thresholds will likely not experience value loss if harvested within five years of initial fire injury, and value loss beyond five years can be reliably predicted to an extent using models presented here. Our results are useful to forest managers for scheduling tree harvests after prescribed burning to minimize value loss in red oak due to fire injury to the lower boles of trees.

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Appendix A

Percent value loss (PVL) in timber product values to butt logs from trees with different fire-scar dimensions (left column, HxD = fire-scar height $*$ fire-scar depth) and diameter at breast height (DBH) measured at 1.37 m above ground level (cm) (top row); due to fire damage. Tabled values developed from Eq. (4).

Scar size HxD	DBH 25	28	31	34	37	40	43	46	49	52	55	58
0	0	0	0	0	0	0	0	0	0	0	0	0
65	2	2	2	1	1	1	1	1	1	1	1	1
194	6	5	4	3	3	3	2	2	2	2	2	1
323	9	8	6	5	5	4	4	3	3	3	2	2
452	13	10	9	7	6	5	5	4	4	3	3	3
581	16	13	11	9	8	7	6	5	5	4	4	3
710	20	16	13	11	9	8	7	6	6	5	5	4
839	24	19	16	13	11	10	8	7	7	6	5	5
968	27	22	18	15	13	11	10	8	7	7	6	5
1097	31	25	20	17	14	12	11	9	8	7	7	6
1226	34	27	22	19	16	14	12	10	9	8	7	7
1355	38	30	25	21	18	15	13	12	10	9	8	7
1484	41	33	27	23	19	16	14	13	11	10	9	8
1613	45	36	29	24	21	18	16	14	12	11	10	9
1742	48	39	32	26	22	19	17	15	13	12	10	9
1871	52	42	34	28	24	21	18	16	14	12	11	10
2000	56	44	36	30	26	22	19	17	15	13	12	11
2129	59	47	39	32	27	23	20	18	16	14	13	11
2258	63	50	41	34	29	25	22	19	17	15	13	12
2387	66	53	43	36	30	26	23	20	18	16	14	13
2516	70	56	46	38	32	28	24	21	19	17	15	13
2645	73	59	48	40	34	29	25	22	19	17	16	14
2774	77	61	50	42	35	30	26	23	20	18	16	15
2903	80	64	52	44	37	32	28	24	21	19	17	15
3032	84	67	55	46	39	33	29	25	22	20	18	16
3161	87	70	57	48	40	34	30	26	23	21	18	17

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