CAUSES AND COSTS OF BOLE WOUNDS IN HARDWOODS—A SYNOPSIS OF THE LITERATURE

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Abstract—Silvicultural practices are known to affect the initiation and development of wounds and wound-related defects. Research on partial-cutting-related wounds has focused on residual stand damage, while wound occurrence associated with prescribed fire has been studied much less. This paper reviews published results of occurrence rates, causes, and costs associated with residual tree wounding owing to these two important practices in hardwood forest management.

INTRODUCTION

Tree wounds are caused by a wide range of natural events and anthropogenic activities and occur in tree crowns, on branches, on the bole, or on roots. Existing information mostly relates to bole wounds as they are more visible, accessible, and considered more economically important.

Wind, ice, heavy snow loads, cold temperatures, lightening, wildfire, sunscald, drought, and flooding all contribute to wounding (Seifert and Woeste 2005). Animals also can cause bole wounds and root compaction. Human-caused tree wounding can be accidental (e.g., equipment contacting trees, careless fire and herbicide application) or purposeful (e.g., farm fence construction, maple syrup tapping, branch pruning, and silvicultural activities).

A review of residual stand damage caused by harvest operations (Vasiliauskas 2001) was predominantly softwood focused. Nyland (1986) reviewed pre-1986 studies of logging damage following thinning of even-aged hardwood stands. Dey's (1994) review of logging impacts concentrated on the damage effects to stand structure and summarizes how damage to trees may affect future tree vigor and quality. None of these papers address the residual stand impacts of silvicultural use of fire.

This review focuses on wound occurrence in residual trees in eastern hardwood forests from prescribed fire and forest operations, emphasizing tree quality and value impacts. Tree response to wounding is a critical aspect of tree and wood quality development included in this review. Tree and stand value impacts attributed to wounding and wound-associated losses in tree vigor and condition are highlighted for stands managed for timber harvest and income.

WOUND OCCURRENCE RATES IN TEMPERATE HARDWOODS

Wound Occurrence, Decay Association, and Likely Causes

An early survey of the amounts and causes of wounding in hardwoods found 47 percent of the trees harvested of eight commercial species in the Appalachian region contained fire wounds. However, harvested trees were "the best trees of the most desirable species" (Hepting and Hedgecock 1937). The critical relationship between basal wounds and decay was elucidated in this paper—only 6 percent of harvested trees lacking basal scars had decay at stump height, compared to 67 percent for trees with wounds.

The entry path of decay fungi in hardwoods was observed in several more recent studies of landscape level wound and decay occurrence rates in the central hardwood region (Berry 1969, 1977, Berry and Beaton 1972a, b*)*. Fire scar associated decay comprised 24 to 48 percent of the infections and accounted for 32 to 63 percent of the affected merchantable volume in these studies. The proportion of decayed trees for which logging damage was the entry path for infection was less certain. Also in the 1970s, bottomland hardwood quality surveys showed 40 percent of harvested trees contained butt rot, with 65 percent of infections attributed to fire scars, indicating fire wounds negatively impacted the quality of 26 percent of trees (McCracken 1977). Most of the non-fire rot infections were attributed to harvesting.

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Berry (1969) and Berry and Beaton (1972a) examined the reliability of visible defect indicators on oaks (*Quercus spp.*) for signifying associated decay—this is key information for timber stand management and sale valuation. In both studies, over 90 percent of open fire scars were associated with underlying decay. Closed fire scar results varied, with 64 percent associated with underlying decay in the Central Hardwood Region (Berry and Beaton 1972a) compared to only 35 percent in Kentucky (Berry 1969). Damaged tops were indicators of wood decay in 50 to 60 percent of trees. Unsound branch stubs indicated decay in 16 to 31 percent of trees. Mechanically injured trees included decay in 10 (Berry 1969) to 26 percent of trees (Berry and Beaton 1972a). These studies were conducted in even-aged, undisturbed stands (except for fire), so damage and decay from forest operations are not represented.

Evidence of tree quality issues affecting tree merchantability in the Northern United States from FIA plots (Morin and others 2016) indicated that 76 percent of trees ≥5 inches diameter at breast height (d.b.h.) were free of significant damage and decay was present in only 16 percent of trees. Less than 3 percent of trees had significant recent logging damage, but earlier logging injuries that subsequently appeared as wounds with decay were indistinguishable from other types of decay. The percentage of hardwood trees with major decay ranged from 35 percent for *Fagus* spp. to 10 percent for *Ulmus* spp., with *Quercus* spp. and *Acer* spp. at 11 and 22 percent, respectively. (Morin and others 2016).

Forest Operations Caused Wounds

Over the past half-century, hardwood silviculture to affect stand structure has become widespread. Prescriptions often involve partial cuts to improve the residual stand, promote the regeneration of desired species, generate income while preserving future income, and create structural diversity for wildlife. Although no studies similar to those cited above (sampling tree damage and decay across wide regions) have been conducted since the mid-1970s, scientists have conducted specific studies looking at the impacts of different types of harvest treatments on residual stand attributes, including wounding.

Wounding rates on residual hardwood stems caused by harvesting operations have been reported as low as 8 percent (Dwyer and others 2004) and as high as 68 percent (Meadows 1993); study designs are as varied as these results. Table 1 summarizes 13 unique studies on residual tree bole damage from forest operations. Other forms of damage are not included because several studies did not evaluate crown and root damage, while those that did used different damage classification systems.

Two studies sampled many logging operations across ownerships: one (18 sites) was conducted in northern hardwoods (Cline and others 1991), and one (101 sites) in central Appalachian forests (Hassler and Grushecky 1999). Bole wound occurrence rates after logging for a range of sites and management prescriptions was about 13 percent in both studies. By contrast, for the other 12 studies in table 1, the overall average wound occurrence rate associated with logging activities was about 18 percent higher.

Factors Affecting Wounding Rates and Severity in Forest Operations

Pre- and post-harvest basal area and wounding rates—Residual basal area (RBA) has been examined as a factor affecting the damage levels in several post-harvest residual stand studies (Clatterbuck 2006, Fajvan and others 2002, Lamson and Miller 1982, Miller and others 1984, Nichols and others 1994, Nyland 1986). Lower RBA treatments resulted in higher levels of residual stand damage in two studies (table 1) (Lamson and Miller 1982, Miller and others 1984). Clatterbuck's (2006) study indicated lower RBA resulted in less bole damage but logging operations were judged to be sub-par. Nichols and others (1994) returned mixed results, but found a direct relationship between initial stand basal area and residual tree damage levels. Nyland (1986) offered "The incidence of damage seems to increase with the intensity of thinning operation." Hence, a likely predictor of the level of residual stand damage is the ratio of initial stand basal area and residual stand basal area.

Wounding associated with felling versus skidding—The distance of residual stems from skid trails was a significant factor in modeling the probability of stem damage in a northern hardwood damage assessment by Nichols and others (1994) comparing manual felling and skidding with a rubber-tired skidder to a mechanical harvest operation using a feller-buncher. The probability of wounding trees located adjacent to skid trails averaged 40 and 60 percent, respectively, for manual and mechanical operations. However, damage to stems caused by feller-buncher skidding declined rapidly as the distance from the skid trails increased with 3 percent of residual trees located 18 feet from skid trails damaged (compared to 15 percent for the manual operation at the same distance; Nichols and others 1994). An evaluation of harvest operations in Missouri (Bruhn and others 2002) included both even- and uneven-aged treatments and showed 74 percent of the injured residual trees (≥10 inches d.b.h.) were located within 6 feet of skid trails and 50 percent of trees proximal to primary skid trails suffered bole injuries. A retrospective assessment of 33 non-controlled harvesting operations in West Virginia showed that 62 percent of the damage occurred during skidding (Egan and Baumgras 2003).

Table 1—Forest operations-caused bole wounding of residual hardwood trees

Study authors and year	Site(s)	Forest type(s)	Number of trees	Treatment(s)	Percent bole wounded			Percent with wounds ≥100 square inches
					Saw timber	All sizes	Pole-timber	
Dwyer and others (2004)	MO; 9 sites 2 treatments	Oak-hickory and oak-pine	8,901	Uneven-aged: q=1.5	----	10	–	–
				Even-aged: intermediate treatment	–	7	–	–
Cline and others (1991)	ME, NH, VT; 18 sites	Northern hardwoods	–	Various as dictated by landowner	–	14	–	–
Hassler and others (1999)	WV; 101 sites	Various throughout State	–	Various as dictated by landowner	9	–	11	4
Clatterbuck (2006)	TN; 1 site, 3 treatments	Oak-hickory	528	12.5% RBA	–	35	–	–
				25% RBA	–	65	–	–
				50% RBA	–	66	–	–
Fajvan and others (2002)	WV; 1 site, 3 treatments	Appalachian hardwood	1,380	12-inch DL	13	–	14	26
				16-inch DL	16	–	19	16
				Shelterwood	22	–	14	16
Johnson and others (1998)	WV; 20 sites	Beech/cherry/maple (11 sites); App. hardwoods (5); oaks (4)	768	Shelterwood:	–		–	28
				Mar-Jun	–	58	–	23
				July-Oct	–	46	–	14
				Nov-Feb		34		
Kelly (1983)	VT; 4 sites	Northern hardwoods	–	Shelterwood	52	–	31	10
				Thinning	74		43	12
Lamson and Miller (1982)	WV; 1 site	Cherry-maple	9,350	45% RBA	–	50	–	14
				60% RBA	–	30	–	7
				75% RBA	–	22	–	5
Lamson and others (1985)	WV; 1 site 4 stands	Appalachian hardwood	1,539	q-value=1.3	11	–	13	2
Meadows (1993)	MS; 1 site	Bottomland hardwoods	–	Improvement cut w/ 75% RBA	42	–	37	36
Nichols and others (1994)	ME; 1 site, 4 treatments	Beech-sugar maple	1,394	48% RBA -skidder	43	–	44	–
				80% RBA -skidder	19	–	29	–
				33% RBA feller-bunch	16	–	18	–
				43% RBA feller-bunch	28	–	37	–
Nyland and Gabriel (1971)	NY	Northern hardwoods	–	Uneven-aged thinning	–	16	–	15
Olson and others (2015)	MO; 1 site 20 stands, 2 treatments	Bottomland hardwoods	1,420	CC w/ residuals	–	7	–	–
				BAR: 20-30 ft^2/a	–	9		
Ostrofsky and others (1986)	ME; 2 sites	Paper birch, beech-oak	–	Heavy thin/with whole-tree harvest	–	29	–	–

App.=Appalachian; RBA=residual basal area; CC=clearcut; BAR=basal area removed; DL=diameter-limit cut.

Damage caused by tree felling was assessed by Miller and others (1984) for thinning treatments in central Appalachian mixed oak-cove stands. Overall, between 26 and 34 percent of the residual stems were bent, leaning, or destroyed by tree felling; however, <3 percent of the residual crop trees (≥11.0 inches d.b.h.) were affected. Between 13 and 25 percent of residual stems had bole injuries and 21 to 30 percent had broken tops—for crop trees the incidence rates were 6 and 2 percent, respectively.

Season of harvest—Residual trees are at greater risk of suffering harvesting-induced damage and future degradation with spring and early summer harvesting; the percentages of trees with sapwood exposed wounds and with large wounds are higher (Johnson and others 1998). Wound occurrence rates on residuals were 35 and 18 percent after summer and winter harvest operations, respectively, in a Maine study (Nichols and others 1994). The wound width to tree circumference ratio indicated larger wounds resulting from summer harvesting. A study in West Virginia evidences this effect with a large difference in the proportion of trees wounded in spring compared to winter harvesting(58 vs. 34 percent) (Johnson and others 1998). Larger wounds (>100 in^2) were significantly more prevalent after spring harvesting (table 1).

Wound location and size—Bole wound size is an important determinant of the probability a tree will recover without significant discoloration and decay. Bole wounds with abraded bark “that remove bark from at least 150 in^2 of trunk surface have a 50 percent chance of developing decay within 10 years” (Nyland 1986). Hesterberg (1957) determined wounds that exposed underlying wood area of ≥100 in^2 were severe. Most studies have used this Hesterberg measure to distinguish the proportion of bole wounds with a significant probability of decay development. As summarized in Table 1, the overall mean percentage of residual trees having wounds ≥100 in^2 is 16 percent.

Prescribed Fire Caused Wounds

Fire effects studies conducted in the eastern hardwood forests of North America have not focused on the quality and value impacts of prescribed fire on residual sawtimber trees. Instead, the studies focused on the effects of prescribed fire on oak regeneration success, the influence of prescribed fire on tree mortality, and the impacts of prescribed fire on residual stand structure and species dynamics. However, wildfire studies prior to 1960 almost exclusively focused on impacts on overstory trees (Brose 2014).

Fire-caused wounds are difficult to tally soon after occurrence. What can be tallied in the first months after fire is the dimensions of the bark burn/char/scorch. To determine wound occurrence requires assessment 2 or more years after the fire. Alternatively, wounds have been assessed through time-intense bole dissection of trees already showing evidence of wounding (Dujesiefken and others 2005, Smith and Sutherland 2006, Smith and others 2001). These studies have furthered our understanding of tree response to heat caused injury, wound closure rates, decay occurrence, and fire history.

Table 2 summarizes the prescribed fire studies conducted in the eastern hardwood region that include estimation of bole damage occurrence. Empty cells in table 2 indicate the variability among these studies. Differences in the way damage/scarring is defined and differences in minimum tree sizes measured also exist. Differences in fire temperatures, stand basal areas, topography, etc. are not captured by this summary. Given these caveats, the overall mean proportion of trees damaged in the seven studies included in table 2 is 41 percent with damage proportions ranging from 21 to 66 percent.

Wounding rates and severity associated with prescribed fires—wounding rates and dimensions (table 2) are affected by many factors; fire intensity and duration are among the most important. Unfortunately, wound sizes are missing for most prescribed fire studies that provide wounding rates. Differences among species in overstory tree susceptibility to wounding caused by fire are largely attributable to the level of protection offered by bark. Bark thickness is the key protective factor, but heat transmission properties can vary among species (Hengst and Dawson 1994, Spalt and Reifsnyder 1962) as can bark regrowth rates. The most important component of bark thickness is the thickness of the outer, corky bark portion (Stickel 1941). The low density of the outer bark provides most of the insulation from fire (Hare 1961). Several North American hardwoods have thick bark but the bark has deep longitudinal fissures between bark ridges. Chestnut oak (*Quercus prinus)* is one such species and has been found to develop fire scars under bark fissures where the bark is thinner (Smith and Sutherland 2001, Sutherland and Smith 2000).

The rate at which bark thickens as a tree grows varies by species, with some species being vulnerable to injury from fire much longer than others. The rate of bark thickening as a function of d.b.h. was modeled for 16 hardwood species by Hengst and Dawson (1994). Overall, their results indicated that upland hardwood species produce thicker bark at a younger age than do lowland species.

Species differences in physiological response to wounding are important in limiting degradation over time. How effectively a given species compartmentalizes injuries to limit deleterious effects has been explained

Table 2—Prescribed fire caused wounding of hardwood stems

Study authors and year	Location	Forest type	No. of trees	Prescribed fire treatment	Mortality proportion Over-story	Mortality proportion All	Damaged proportion Over-story	Damaged proportion All	Mean scar width (inches) or circum (%)
Wendel and Smith (1986)	Central Appalachians	Oak-hickory	~2,415	Spring	5%	–	66%	–	–
Brose and Van Lear (1999)	VA	Piedmont: oak-hickory	733	Spring	19%	–	31%	–	–
				Summer	0%	–	21%	–	–
				Winter	0%	–	22%	–	–
Paulsell (1957)	MO	Ozark uplands: oak-hickory	1337	Annual burn	5%	–	–	27%	–
				Periodic burn	3%	–	–	34%	–
Guyette and Stambaugh (2004)	TN	Upland hardwoods: post oak	–	Fall 1997	–	–	35%	–	Circum.=10
				Spring 2000	–	–	62%	–	Circum.=12
				Spring 2003	–	–	65%	–	Circum.= 8
Stevenson (2007)	MO	Ozark uplands: oak-hickory-shortleaf pine	3.754	Southwest facing slopes	–		–	64%	r. oak: 11 bl. oak: 11 wh. oak: 9 post oak: 8 hickory: 7
				Northeast facing slopes	–	–	–	52%	
Ward and Brose (2006)	CT	Eastern oak	3,476	7 prescribed fires	–		Oak: 25%		–
							Non-oak: 28%		–
Wiedenbeck and others (2017)	WV	Mesic upland hardwoods	1,777	Shelterwood-burn - 2 spring fires	–	9%	–	33%	–

Circum.=circumference.

by Hepting (1935), Shigo (1966, 1984), Smith and Sutherland (2001, 2006), and Smith and others (2001). Quick wound closure after injury is a related factor that influences the vulnerability of trees to further wounding; radial growth rates can differ substantially among species. For forest managers using prescribed fires to promote oak regeneration, the application of more than one prescribed fire to affect desired outcomes means that wound closure rates for mid- and overstory trees are particularly meaningful.

One of the first North American studies of eastern hardwood tree species response to fire was conducted by Nelson and others (1933). Their study of fire wounds after a severe wildfire indicated important species differences in wound size. They found that yellow-poplar was distinctly more resistant to wounding by fire than scarlet oak (*Quercus* coccinea) when considering larger diameter trees with other species intermediate in resistance.

Efforts to estimate the impact of a fire on residual tree mortality and quality soon after fire occurrence require that the relationships between bark discoloration and future tree outcomes are identified since it can take 2 years before wound severity and mortality can be detected. Loomis (1973) modeled mortality and wound size based on bark scorch measurements in a broad-scale study of trees in Missouri, Pennsylvania, and West Virginia and predicted the height and width of wounds for red oak (*Quercus rubra*), black oak (*Quercus velutina*), ash *(Fraxinus* spp.), hickory (*Carya* spp.), and scarlet oak would be 90 and 60 percent, respectively, of the height and width of bark blackening measured after a dormant season fire. For white oak (*Quercus alba*), post oak (*Quercus stellata*), and chestnut oak (*Quercus montana*), the predicted height of the wound that would develop was 70 percent of the height of the blackened bark. Species differences in the probability of being injured by fire were explored in a Missouri Ozark forest by Stevenson and others (2008). They concluded the species-based risk of wounding from fire was: “red oaks > black oak = white oak > post oak = hickories > shortleaf pine” (*Pinus echinata*). These two studies provide evidence that species in the white oak subgenus are more fire tolerant than those in the red oak subgenus.

CONSIDERING LOGGING WOUNDS VERSUS FIRE WOUNDS

What is less known is what, if any differences there may be in tissue damage and wound response for trees subjected to fire wounding compared to abrasion-type wounds. Thicker bark is acknowledged to be more protective than thinner bark. Most studies of this protective capacity have been studies of how bark insulates trees from the heat of fires. That thicker bark also provides greater protection for trees from other types of injuries is logical. Wood and bark strength properties increase with increasing specific gravity, therefore, the outer bark which has lower specific gravity, provides insulation from heat injury but offers less protection from certain types of applied stress.

Smith and Sutherland (1999) dissected tree scars on the lower bole of oaks and concluded that the appearance of historical wounds is not distinctly different for trees injured by fire compared to other wounding agents. They also determined that the presence of charcoal in a wound is not definitive of the wound having been caused by fire. Shigo (1966) observed that an important difference between fire-caused wounds and logging wounds is that fire caused wounds are less variable, typically occurring at the base of the butt log with decay developing upward from the wound.

Closure of Wounds

Wound closure, the process by which exposed xylem is gradually covered by new wood and bark, reestablishes the bark covering of wounded regions to provide the tree needed protection from insects, bacteria, and fungi. Species with faster radial growth are able to close wounds more quickly than slow-growth species. Wounds that are wider require longer to close than narrower wounds. For example, bole wounds in sugar maple have a 50 percent chance of developing decay after 10 years if the wound size is >150 in^2 but an 80 percent chance if the wound exceeds 250 in^2 (Hesterberg 1957).

In-woods observation of wound closure rates based on remeasurement of injured stems were conducted by Smith and others (1994) and Jensen and Kabrick (2014). Smith and others (1994) collected remeasurement data 5 and 10 years after wound initiation for bole wounds on 70 to 80 year-old residual trees. For northern red oak, white oak, and yellow-poplar (*Liriodendron tulipifera*), about half of the wounds with initial exposed wood areas ≤100 in^2 had closed after 5 years. No wound closure was recorded for larger wounds. After 10 years, 88 percent of the smaller wounds but only 19 percent of larger wounds were closed (Smith and other 1994). The wound closure results reported by Jensen and Kabrick (2014) were based on a single resurvey of wounded trees 13 years after harvest operations and included trees ≥4.5 inches d.b.h. Overall, 76 percent of the wounded trees no longer had open bole wounds. The Jensen and Kabrick (2014) sample size permitted species-based comparisons to be made: white oak (92 percent), scarlet oak (82 percent), black oak (58 percent), hickories (36 percent), and shortleaf pine (17 percent) were the most to least successful in closing wounds. For all tree species and wound sizes combined in the Smith and others study, 59 percent of bole wounds were closed after 10 years compared to 76 percent closed after 13 years in the Jensen and Kabrick (2014) study.

Quality, Grade, and Value Impacts Associated With Wounds

A foundational study on the impact of harvest-based wounds on quality and log and lumber grade recovery was conducted by Hesterberg (1957) on sugar maple (*Acer saccharum*). Logs with wounds suffered a mean value loss of 11 percent when evaluated 10 years after wounding, with 9 percent of the logs reduced in grade (Hesterberg 1957). However, the mean value loss of the lumber sawn from these logs was only 3 percent. In another study of sugar maple (Ohman 1970), value losses associated with wounds from harvest operations were lower after 10 years, 1 percent for logs and 3 percent for lumber. Ohman (1970) evaluated yellow birch (*Betula alleghaniensis*) recovery as well and reported 12 and 4 percent log and lumber value losses, respectively.

Estimated log grade impacts for butt logs of residual trees were higher in a study of basal area retention differences in the Southern Appalachians (Clatterbuck 2006) with 45 percent of the bole damaged trees judged to have damage levels sufficient to cause a drop in log grade. Johnson and others (1998) study of shelterwood with reserves stands in the Appalachians evaluated butt log grade changes in residual trees attributable to logging damage with similar results to Hesterberg (1957) and Ohman (1970). About 2 percent of the butt logs lost grade 2 to 5 years after harvesting. With assessments conducted only 2 to 5 years after wound occurrence, further degradation owing to decay development associated with some wounds could be expected.

A study of wildfire impacts on product value based on a range of tree sizes and geographic locations (thus fire intensities) in oak-hickory forests determined value and volume losses were related to wound height, width, age, and tree d.b.h. (Loomis 1973, 1974) with R^2 levels for log and lumber value loss equations of 0.54 and 0.45, respectively. Loomis (1989) composed a look-up table for estimated volume loss due to basal fire wounds based on his earlier research.

Wildfire caused stumpage value losses for hardwood stands informs the discussion of prescribed fire use in oak-hickory forest types. Reeves and Stringer (2011) determined, based on 10 sets of matched stands with one burned and the other unburned, that the timber value loss from wildfires ranged from 5 to 65 percent with an average loss of 47 percent. Of the estimated loss, 28 percent was attributed to cull volume while 72 percent was related to structural changes including tree mortality and changes in species distribution and size classes of timber (Reeves and Stringer 2011). A coarser approach was taken by Wood (2010) in assessing value loss to sawtimber in West Virginia stands that had undergone from 0 to 6 wildfires. Value decline increased with increasing fire exposure ranging from a 10 percent decline in sawtimber value for stands subject to one wildfire to 53 percent for stands following six wildfires (Wood 2010). The corresponding declines in sawtimber volumes determined by Wood ranged from 6 percent to 55 percent. The stand value effects determined by Reeves and Stringer (2011) and Wood (2010) align well with each other with value losses ranging from 5 percent to 65 percent in the former study and from 6 percent to 55 percent in the latter.

Prescribed fire impacts on the quality and value of residual trees have received little attention. Studies have been conducted on oaks in Missouri (Knapp and others 2017, Marschall and others 2014, Stambaugh and Guyette 2008) and at a single site in West Virginia associated with shelterwood-burn study (Wiedenbeck and Schuler 2014, Wiedenbeck and others 2017). This dearth of information, together with the increased use of prescribed fire in eastern hardwoods, has led to new research activities focused on this subject (Stanis and Saunders 2017).

Analysis of 41 basal tree sections containing fire scars caused by a prescribed fire that occurred 6 years earlier provided averages for scar size (41 cm^2), woundwood volume (24 cm^3), decay volume (27 cm^3) and discolored wood volume (27 cm^3) for the sample of white, black, and scarlet oak stems (Stambaugh and Guyette 2008). Twenty percent of the butt logs with fire scars in this study dropped in grade due to the fire injury. Tree and lumber volume and value loss estimates for red, black, and scarlet oak trees affected by fire were measured by Marschall and others (2014). The average lumber volume and value losses per tree were 4 and 10 percent, respectively, with many boards dropping in lumber grade but not in volume.

Isolating the wood quality changes attributable to two prescribed fires that were conducted 5 and 8 years prior to tree harvest indicated only minor effects of prescribed fire on lumber quality with 16, 13, 12, and 7 percent of the lumber recovered showing any sign of fire damage for red maple (*Acer rubrum*), red oak, white oak, and yellow-poplar, respectively (Wiedenbeck and Schuler 2014). Minor indicators included mineral stain (red maple), surface checking (red and white oak), and incipient decay. Recent, low intensity fire exposure appears to have very little impact on the quality and value of hardwood lumber recovered from affected stems based on limited research.

The effects of prescribed fire on residual stand value rather than tree value has been given less attention. The one known study was based on Marschall and others' (2014) model. Knapp and others (2017) estimated stand value loss for areas that had a history of prescribed fires to be <3 percent. However, total stumpage value of these stands was substantially lower than the stumpage value of unburned stands—approximately 30 percent (Knapp and others 2017). This higher figure includes structural changes in the stands—species and tree size class shifts—and aligns with the results of Reeves and Stringer (2011) in their study of wildfire impacts. Unfortunately, Knapp and others' (2017) work is based only on red oak species from Missouri.

CONCLUSIONS

A literature review of residual tree wounding from two important eastern hardwood silvicultural practices, timber harvesting practices and prescribed fire, shows a lack of contemporary study related to fire-caused wounds and the effects of prescribed fire on the quality and value of residual trees. Knowledge of wound occurrence is important because of subsequent degradation caused by organisms that invade the tree through exposed sapwood, and the negative effects of tree decay. Multiple surveys of landscape level wounding rates and causes along with evaluations of linked decay amounts and effects, from the 1970s, indicated that fire-caused wounding and decay were more prevalent than wounding from harvesting activities. Since these studies were conducted before the era of prescribed fire use in eastern forests contemporary surveys are needed. Several studies provide information on the timber and product value impacts of wounds associated with mechanical damage. Until recently, studies of the impacts of wounds caused by prescribed fire were lacking. As the knowledge base of prescribed fire impacts on merchantable timber yields grows, comparing the residual tree damage and value impacts of forest operations and prescribed fire will be constructive.

Wounds sustained by residual sawtimber in partial cut harvesting operations are largely the result of skidding activity rather than tree felling. Damage assessments post-logging have been inconsistent in dealing with wounding of roots and tree crowns, but bole wounds to residual sawtimber, especially wounds to the lower bole, are uniformly reported. Residual tree wounding rates ranged from 7 to 66 percent, with rates of 15 to 35 percent commonly cited.

Wounds create tree health vulnerabilities by exposing the sapwood. Wounds larger than 100 to 150 in^2 have been categorized as "major." For wounds caused by logging operations, about 15 percent of residual stems suffer from major wounds. Studies of prescribed fire caused wounds have not used the same classification. Particularly important in silvicultural systems employing prescribed fire is wound width since wider wounds take longer to close. With many regeneration and restoration objectives dependent on multiple prescribed fires, wound closure before repeat fires is important for forests managed for future timber income. Since many pathogens that attack exposed sapwood are moisture dependent, wound shape and location also can affect decay development. Wounds that hold water and wounds in contact with the ground are potentially more vulnerable to decay organisms.

More information is needed on the effects of prescribed fire on the quality and volume of stems of different species and sizes as time elapses before the stems are finally harvested. Published results to-date have been based on small sample sizes in only two locations. For forests managed with timber production and income goals included as priority objectives, this information is essential.

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