Hardwood management, tree wound response, and wood product value

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ABSTRACT
Hardwood forest management practices may wound trees and initiate defects that reduce wood quality and value. Damage to the lower bole of residual stems during harvest operations has been heavily researched. Wounding from prescribed fire has been the subject of more recent studies. Injuries caused by harvesting and prescribed fire activities to tree roots and crowns are in shorter supply. Also, the relationship of wounding to wood value is less well-documented. The effects of wounding on wood value is an interaction among wound position, frequency, severity, and the constitutive and induced processes of tree protection and defense. Foresters should be informed about the consequences of tree wounding and management practices that affect wood quality and economic value. This paper reviews published observations on the occurrence, severity, and costs associated with wounding of potential crop trees as a result of forest operations and prescribed fire.

Key words: compartmentalization, wound closure, hardwood quality, prescribed fire, stand entry, harvest operations

RÉSUMÉ
Les travaux d'aménagement chez les feuillus peuvent occasionner des blessures aux arbres et provoquer des défauts qui diminuent la qualité et la valeur du bois. On compte plusieurs études sur les dommages que causent les opérations de récolte à la bille de pied des arbres résiduels. Des études plus récentes se sont intéressées aux blessures qu'occasionne le brûlage dirigé. Les blessures liées à la récolte et aux activités de brûlage dirigé sur les racines et la cime des arbres sont passablement moins documentées. On connaît également assez peu le lien entre les blessures et la valeur du bois. Les effets des blessures sur la valeur du bois résultent de l'interaction entre la position des blessures, leur fréquence et leur gravité ainsi que les processus constitutifs et induits de protection et de défense chez l'arbre. Il serait souhaitable que les forestiers connaissent les conséquences des blessures aux arbres et des traitements qui affectent la qualité et la valeur économique du bois. Cet article fait le bilan des observations documentées sur la fréquence, la gravité et les coûts liés aux blessures aux arbres d'avenir résultant des opérations forestières et du brûlage dirigé

Mots-clés: compartimentage, formation de callus, qualité des bois francs, brûlage dirigé, intervention dans un peuplement, opérations de récolte

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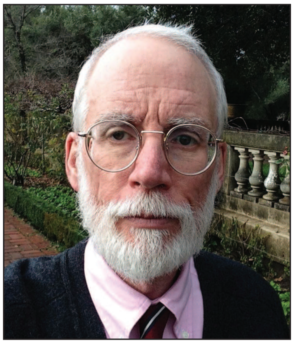

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Introduction

This review summarizes research on the wounding of crop trees caused by active management of temperate hardwood forests and the effects of those wounds on the economic value of timber. We consider wounds caused by mechanical injuries that are the direct result of silvicultural activities. Mechanical injuries indirectly caused by stand manipulations such as wind damage and ice breakage, are not within the scope of this review. Neither are chemical, temperature, nor moisture-caused injuries addressed. The management practices that can cause wounding and that are considered here include the effects of felling and skidding on residual trees and the effects of prescribed fire on the standing crop in stands managed for timber harvest and income. Since the survival, health, and potential value of wounded trees are related to both the nature of the wound and the ability of the wounded tree to recover, we describe the response of living sapwood to wounding including wounding caused by wildfire.

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Hardwood management practices such as mechanized stand entry for harvest or road construction can wound trees and reduce wood quality and value. Such injury on residual trees is often referred to collectively as "logging damage" and the effects as "post-harvest decadence".

A review of damage to trees caused by forestry operations (Vasiliauskas 2001) provides a valuable synthesis of information from studies conducted in North America and Europe related to residual stand damage. The focus of the review was on wounding levels and subsequent decay/discoloration for different harvesting intensities. However, fewer than 10% of the papers cited by Vasiliauskas (2001) address hardwood species. Nyland (1986) reviewed studies on logging damage levels measured after thinning of even-aged hardwood stands. The Nyland paper provides an excellent synthesis of studies conducted prior to 1986 on logging-induced residual stand impacts. A review of logging impacts on residual trees, soil, wildlife, and aquatic systems by Dey (1994) concentrates on the damage effects on stand structure. The paper also provides a succinct summary of available information on how damage to different parts of a tree may affect future tree vigour and quality. None of these papers address the residual stand impacts of silvicultural use of fire.

Timber value and tree wounding

For hardwood forests managed for high-value wood products, injury, infection, and decay can reduce wood quality and economic value along the entire processing stream from standing timber, logs on the landing, and in primary and secondary operations and markets (Rast *et al*. 1973, Cecil-Cockwell and Caspersen 2015). Wound associated defects that impact merchantable tree and log volume are "scale" defects while value reducing defects are "grade" defects (Rast *et al.* 1973). When a wound leads to wood decay, a scale defect is present. Wounds that are less significant may lead to only a minor grade defect (e.g., a small area of callus tissue) or a minor area of discoloured wood.

However, injuries to trees are not only important for the volume, grade, and colour impacts they can bring about, they also can lead to tree mortality, loss of tree vigour, and structural changes in forest composition (Loomis 1973, Walters *et al*. 1982, Reeves and Stringer 2011, Guillemette *et al*. 2008). Understanding differences in tree response to wounding caused by silvicultural activities among species, tree vigour classes, stem size classes, has wide-ranging implications for forest landowners and managers to comprehend and apply.

Evidence of tree quality issues affecting tree merchantability in the northern U.S. (24 states) taken from FIA plots visited between 2009 and 2014 (Morin *et al*. 2016) indicates that 76% of trees > 5-in dbh were considered to be free of significant damage. Decay was the most commonly tallied type of significant damage (16% of trees). Less than 3% of trees had significant recent logging damage (bark stripping and crown damage from recent operations), but logging injuries from years prior that subsequently appeared as wounds with decay were not distinguishable from other types of decay. For hardwoods, the percentage of trees with significant decay ranged from 35% for the genus *Fagus* to 10% for the genus *Ulmus*. The commercially important genera *Quercus* and *Acer* had evidence of damaging decay on 11% and 22% of tallied trees, respectively (Morin *et al*. 2016).

Generally, greater economic value is given to clear, unstained wood in normally "white-wooded" species including maple (*Acer* spp.), birch (*Betula* spp.), sweetgum (*Liquidambar styraciflua*), sycamore (*Platanus occidentalis*), and beech (*Fagus sylvatica*) (Cassens 1999, Wiedenbeck *et al.* 2014). In fact, the importance of colour in the valuation of hardwood timber was a major impetus behind research on the physiological basis for variation of wood colour (Shigo and Hillis 1973, Shigo 1984).

Tree response to injury and infection

Hardwood value is especially affected by wounds to the merchantable bole that kill portions of the vascular cambium. The vascular cambium is the thin layer of cells to the outside of the wood and to the inside of the bark that divide to form new cells that increase stem girth. Secondary xylem formed to the inside and secondary phloem formed to the outside of the vascular cambium matures to become wood and inner bark, respectively. Wounds that kill the vascular cambium for some portion of the stem circumference disrupt translocation, induce wood discoloration (staining), and facilitate infection by wood-destroying fungi (Shigo 1984, Smith 2006). Wounding stimulates physiological shifts in the tree to reduce the impact of injury and infection (Smith 2015). These shifts can result in the formation of oxidized pigments in wounded sapwood that stain and reduce hardwood value.

Compartmentalization

The patterns of wood discoloration, infection, and decay are explained by features of compartmentalization (Smith and Shortle 1998). Compartmentalization is the boundary-setting processes of tree growth and defence that resist the spread of injury and the loss of normal function such as water conduction (Shigo 1984, Smith 2006, Shortle and Dudzik 2012). The position and the timing of boundary formation determines the volume of wood affected by staining, eventual decay, and reduced economic value.

In living trees, intact sapwood resists the spread of active aerobic infections such as those caused by most wood decay fungi, through the maintenance of high moisture content. That high moisture content can deter decay activity may seem at odds with the simple observation that decay of wood in service is often attributed to moisture from ground contact or in structures. The ponding or submersion of logs is a long-established method to preserve the integrity of harvested trees. In living sapwood, higher moisture content excludes free oxygen necessary for wood decay (Boddy and Rayner 1983).

The water in the conducting vessels of both hardwood and softwood is usually under tension while being pulled up from the roots, through the bole and branches, and into the foliage. This flow is especially vulnerable to "air-seeding" and the introduction of emboli or bubbles (Tyree and Sperry 1989). Emboli break the flow of water, aerate the wood, and cause drying which kills living wood cells. The living sapwood cells occlude injured vessels through formation of tyloses, plugs, and gum that resist the axial spread of emboli and wood aeration (Bonsen and Kučera 1990). In fire injury, heat in surviving sapwood causes deformation of xylem cells that reduced hydraulic conductivity without hydraulic isolation, resulting in increased possibility of embolism formation (Michaeletz

2018). The living wood cells at the margin of the destroyed wood tissue also produce suberin and anti-microbial phenolic compounds that provide waterproofing to support hydraulic integrity and to slow the growth of invasive fungi (Shortle 1978, Pearce and Woodward 1986, Oliva *et al.* 2010).

Species differ in their ability to compartmentalize the effects of injury through constitutive and induced anatomical and physiological features that resist the spread of impaired function and infection by microorganisms. Varying effectiveness in barrier zone formation to resist the outward spread of decay has been well explained by Hepting (1936), Shigo (1966, 1984), Schwarze *et al.* (2000), Smith and Sutherland (2001, 2006).

For some hardwoods such as species of oak and cherry, heartwood is formed by the deposition of antimicrobial phenolic compounds and the withdrawal of the network of living sapwood cells (Taylor *et al.* 2002). For these tree species with decay-resistant heartwood clearly marked by a darker colour, greater value is assigned to the darker heartwood. Although a certain amount of folklore and myth as well as scientific uncertainty remains concerning heartwood formation, heartwood results from the aging or maturation of wood tissues (Shigo and Hillis 1973). Pre-programmed cell death of living sapwood results in the conversion of primary metabolites and sugar into secondary compounds that to some degree resist the spread of microorganisms and processes of wood decay (Smith 2015). This strategy reduces the nutritional burden on the tree by reducing the volume of living sapwood that requires nutrition.

In contrast, the stained core or "heart" of merchantable maple, birch, and sweetgum varies in size and frequently results in decreased value of the wood for products. For these diffuse-porous species, wood discoloration is in response to injury and infection rather than age or maturation. In the absence of significant wounding events, these trees produce relatively high-value clear sapwood or "whitewood" with only a small core of discoloured wood. Consequently, the size of the column of the wound-initiated discoloration (referred to here as discoloured wood) reflects the wound history and growth rate of injured trees. Discoloured wood varies in durability in service relative to sapwood of the same species, but does not have the durability of heartwood (Hart and Johnson 1970, Smith and Shortle 1988).

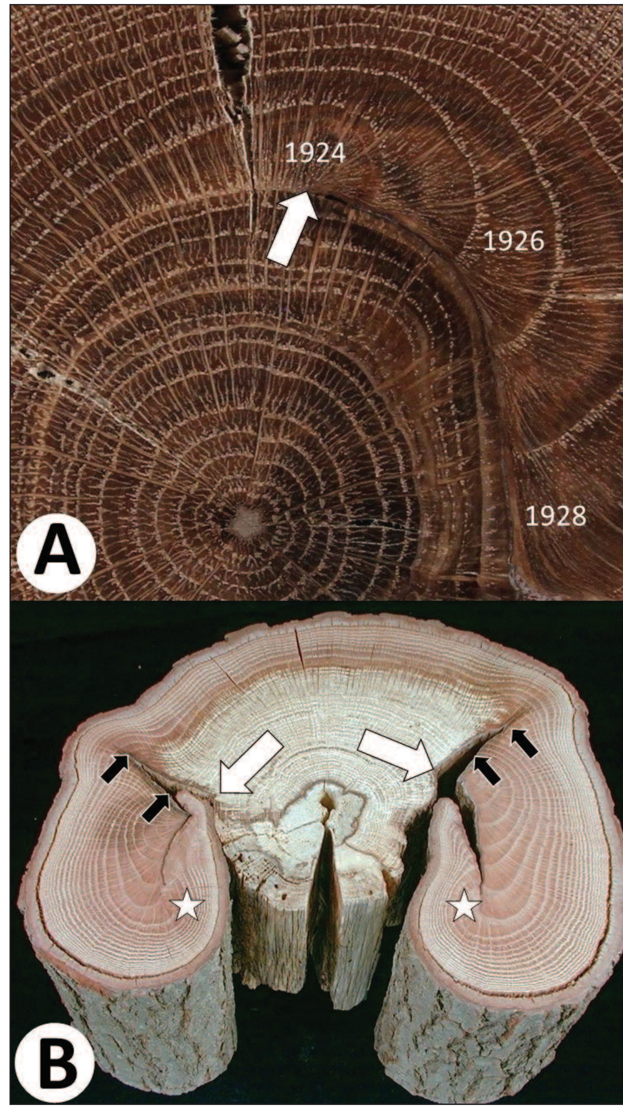

Fig. 1. Transverse section of wound closure in oak. **(A)** This white oak was injured by fire in the dormant season prior to the 1924 growing season. One tangential edge of the wound is marked (white arrow). Localized wood production was stimulated adjacent to the wound with very wide rings for 1924–1928. **(B)** This red oak was injured and the vascular cambium killed for more than fifty percent of the stem circumference (white arrows). Wide rings of woundwood (referred to as "woundwood ribs") were formed at the margins of the wound and eventually curled into the void produced by wood decay. As the curled "ramshorn" (white stars) continued to grow against older wood, radial cracks formed in the stem (black arrows).

Closure

While resistance to the loss of healthy wood from injury and infection comes from compartmentalization, tree recovery from wounding involves wound closure. Wound closure results from the production of new wood, usually at the wound margins, that closes over the killed vascular cambium and wood. These woundwood ribs often contain wider annual rings than those from unwounded portions of the stem (Fig. 1A). The most successful example of closure occurs when the opposing ribs of woundwood meet with the restoration of the circumferential continuity of the vascular cambium. This enables radial growth to continue outward with the opportunity to produce clear, high-value wood. Also, closed wounds reduce activity of wood decay fungi by reducing aeration and the oxygen levels required for wood decay. Occasionally, opposing woundwood ribs meet, forming a bark seam without restoration of circumferential continuity. Woundwood ribs can grow into stem cavities, resulting in "ramshorning", also with without restoration of cambial continuity (Fig. 1B).

Frequency of occurrence of wounds in hardwoods

An early survey of the amounts and causes of wounding in hardwoods indicated that 47% of the boles of harvested trees of eight commercial species in the central and southern Appalachian region contained fire wounds (Hepting and Hedgecock 1937). In contrast, lightning-caused wounds were present on only 0.6% of trees and other types of wounds tallied on less than 2% of trees. The authors noted that only trees being harvested were tallied and harvesting was generally constrained to "the best trees of the most desirable species." This study revealed the critical relationship between basal wounds and decay – only 6% of all harvested trees that lacked basal scars showed decay at stump height while 67% of the trees that had wounds contained decay (Hepting and Hedgecock 1937). More recent research suggests the unaccounted for proportion of the decay in the Hepting and Hedgecock study was likely due to infections from wounded woody roots (Shigo 1984, Schwarze *et al*. 2000).

Somewhat more contemporary surveys of landscape level wound and decay occurrence rates were conducted by Berry (1969) for upland oak in Kentucky, Berry and Beaton for oak (1972a) and hickory (1972b) in the central hardwood region, and Berry (1977) for yellow-poplar, maple, black gum and ash in the same region. Decay associated with fire scars made up between 24 and 48% of the infections and accounted for between 32 to 63% of the affected merchantable volume in these four studies (Table 1). The proportion of decayed trees for which logging damage was thought to be the entry court for the infection was less easily identified in these studies. Mechanical injuries, damaged tops, branch bumps, parent stumps, and root damage, defects that can be caused by logging activities—combined they comprised less than 25% of the infection courts in these four studies (Table 1). For bottomland hardwoods, 40% of harvested hardwood trees contained butt rot of which 65% of infections were attributed to fire scars and the remainder to harvesting activities (McCracken 1977).

The Berry (1969) and Berry and Beaton (1972a) studies examined how reliable visible defect indicators on the tree were in signifying underlying, associated decay—for timber stand management and improvement as well as timber sale valuation this is key information. In both of these studies of oak, over 90% of open fire scars were found to be associated with underlying decay. Closed fire scar results varied somewhat with 64% associated with underlying decay in the Central Hardwood Region oak study (Berry and Beaton 1972a) but only 35% associated with decay in the Kentucky oak dissection study (Berry 1969). The other external damage that was an indicator of decay was mechanical injury with between 10 and 26% of mechanically injured trees having associated decay (Berry 1969, Berry and Beaton 1972a).

These broad area surveys of tree damage and decay occurrence would seem to indicate that wounds caused by forest operations associated with stand structure manipulations are relatively inconsequential. For example, if decay associated with all root wounds, broken tree tops, branch bumps, parent stumps, and mechanical damage in the four studies shown in Table 1 were attributable to forest operations/stand manipulations, (which is highly unlikely), the proportion of all decayed volume that could be ascribed to these operations would be about 25%. Simply averaging the decay proportion associated with fire for the four decay surveys (Berry 1969, 1977; Berry and Beaton 1972a, 1972b) indicates the fire-caused decay was about twice as much (48%; Table 1). Notably, all four of these studies were conducted in even-aged, undisturbed stands (except for fire). Damage and decay associated with stand structure manipulations such as thinning to specified residual basal areas and shelterwood establishment cuts are not represented by these results.

Management practices and tree wounding

Logging and thinning operations

Over the past half-century, hardwood silviculture to affect stand structure has become more widely used and studied. These silvicultural prescriptions often involve partial cuts to improve the residual stand, promote the regeneration of

Table 1. Comparison of results reported by Berry (1969, 1977) and Berry and Beaton (1972a, 1972b) as to the likely damage sources providing pathways for decay fungi to enter hardwoods

	Central hardwood oaks		Kentucky oaks		Central hardwood hickories		Central hardwood other species[a]	
	Proportion of infections	Proportion of infected volume	Proportion of infections	Proportion of infected volume	Proportion of infections	Proportion of infected volume	Proportion of infections	Proportion of infected volume
Infection court				%				
Fire scars	24	40	26	32	48	57	29	63
Dead branch stubs	22	13	14	10	<5[b]	–	8	4
Branch bumps	13	11	6	5	<5	–	–	–
Insect wounds	10	5	16	9	<5	–	–	–
Parent stumps	9	9	8	12	<5	–	8	11
Mechanical injuries	6	4	4	4	5	5	13	5
Open branch stub scars	5	7	6	13	8	20	–	–
Damaged or dead tops	5	7	5	5	<5	–	10	9
Roots	4	3	4	2	<5	–	n/a[c]	n/a[c]
Woodpecker injuries	1	1	4	2	<5	–	n/a[c]	n/a[c]
Unknown	–	–	3	2	22	6	9	3

[a]Other species examined by Berry (1977) included yellow-poplar (n=22), red maple ((n=29), black gum (n=14), sugar maple (n=8), and ash (n=4).

[b]<5 used because the hickory sample was small and for the less important infection courts, the less common infection courts had very minor occurrence rates.

[c]Root and woodpecker damage not detailed in this study.

desired species, generate income while preserving future income, create stand structural diversity for wildlife, and to serve other objectives. Many wide-ranging studies on the impacts of different types of harvest treatments on residual stand attributes, including wounding, have been conducted. Wounding rates on residual hardwood stems caused by forest harvesting operations have been reported as low as 8% (Dwyer *et al*. 2004) and as high as 81% (Clatterbuck 2006).

The design of the studies conducted on logging-caused wounds is as varied as these results. In some of these studies, a large sample of uncontrolled, post-harvest assessments of logged sites provides information on the impacts of current practice across ownerships (Cline *et al*. 1991, Hassler *et al*. 1999). In others, the silvicultural treatments are highly controlled and limited to a single site (e.g., Lamson *et al*. 1985, Meadows 1993, Nichols *et al*. 1994, Fajvan *et al*. 2002, Olson *et al*. 2015). Even more confounding are the differences in how researchers defined and measured wounds and which portions of the tree they included in their evaluations. Fifteen unique studies on residual tree damage resulting from forest operations are summarized in Table 2.

The two studies that sampled many logging operations across ownerships provide residual tree damage level estimates based on actual practice. These studies, one conducted in northern hardwoods (Cline *et al*. 1991, 18 sites), the other in central Appalachian forests (Hassler *et al*. 1999, 101 sites), yielded remarkably similar results. Both studies indicated the wound occurrence rate after logging for a range of sites and management prescriptions was about 15%. A third study of both even and uneven-aged harvest treatments using 26 logging contractors found wounding to be between 8 and 11%. By contrast, for all of the studies noted in Table 2, the overall average wound occurrence rate associated with logging activities was approximately 34%, about 20% higher than the rate recorded in these two survey-based studies of multiple operations.

Pre- and post-harvest basal area and wounding rates

Residual basal area has been examined as a factor affecting the damage levels seen in the post-harvest residual stand in several studies (Lamson and Miller 1982, Miller *et al*. 1984, Nyland 1986, Nichols *et al*. 1994, Fajvan *et al*. 2002, Clatterbuck 2006). In two of these studies, lower residual basal area treatments resulted in higher levels of residual stand damage (Table 2; Lamson and Miller 1982, Miller *et al*. 1984). The opposite result was derived in the Clatterbuck (2006) study but that logging operation was judged to be a sub-par felling job with poorly laid out skid trails. Nichols *et al*. (1994)

Table 2. Forest operations caused wounding of residual hardwood stems

Study authors and year	Forest Type	Treatments	Proportion wounded[a] (%) Saw timber	All stems	Pole timber	Severe wounds[b] (>650cm^2) (%)	Location of wounds
Effect of varying residual basal area							
Clatterbuck (2006)	Oak-hickory	12% RBA[d] 25% RBA[d] 50% RBA[d]	– – –	43 80 81	– – –	– – –	69% bole 19% crown 12% both
Kelley (1983)	Northern hardwoods	40% RBA[d, g] 60% RBA[d] 80% RBA[d]	52 64 83	– – –	31 40 47	10 13 12	77% bole 23% crown
Lamson and Miller (1982)	Cherry-maple	45% RBA[d] 60% RBA[d] 75% RBA[d]	– – –	50 30 22	– – –	14 7 5	Only bole damage assessed
Lamson *et al*. (1985)	Appalachian hardwoods	80% RBA[d] with q-value=1.3	14	–	17	2	76% bole 24% crown
Meadows (1993)	Bottomland hardwoods	7% RBA[d]	68	–	60	36[e]	32% bole 3% crown 35% root 30% multiple
Nichols *et al*. (1994)	Beech-sugar maple	48% RBA[d] with skidder 80% RBA[d] with skidder	45 20	– –	46 31	$\bar{x}$=4 581 cm^2	Only bole damage assessed
		33% RBA[d] feller-buncher 43% RBA[d] feller-buncher	17 19	– –	19 39	$\bar{x}$=3 890 cm^2	Only bole damage assessed

(continued)

Table 2. *(continued)*

Study authors and year	Forest Type	Treatments	Proportion wounded[a] (%) Saw timber	All stems	Pole timber	Severe wounds[b] ($>650cm^2$) (%)	Location of wounds
Shelterwood, diameter-limit harvests, species specific, etc.							
Fajvan *et al.* (2002)	Appalachian hardwoods	12-in DL[d] 16-in DL[d] Shelterwood	13 16 22	– – –	37 19 14	26 16 16	75% lower bole 27% upper bole and roots
Olson *et al.* (2015)	Bottomland hardwoods	CC[d] with residu7als	–	46	–	–	15% bole 85% crown[f]
		BAR[d] 20–30 fts/acre	–	15	–	–	60% bole 40% crown[f]
Tavankar *et al.* (2017)	Caucasian alder (*Alnus subcordata*)	84% RBA[d]	18	<9	–	–	Only bole damage assessed
Broad area survey of harvest damage levels							
Cline *et al.* (1991)	Northern hardwoods	Various as dictated by landowner	–	14	–	–	12% bole 2% roots
Dwyer *et al.* (2004)[c]	Oak-hickory and oak-pine	Various even-aged treatmentsc Various uneven-aged treatments	– –	7 10	– –	– –	98% bole 1% crown 1% roots
Hassler *et al.* (1999)	Appalachian hardwoods	Various as dictated by landowner	15	–	17	4	41% basal 22% bole 18% crown 19% root
Effect of harvesting equipment							
Egan (1999)	Appalachian hardwoods	22% RBA[d] using skidder 20% RBA[d] using shovel logging		32 41	– –	9 9	Only bole damage assessed
Nicholls *et al.* (1994)	Beech-sugar maple	See study details presented in prior section of table		– –	– –	– –	– –
Effect of season of harvest							
Johnson *et al.* (1998)	Beech-cherry-maple; Appalachian hardwoods; mixed oaks	Shelterwood harvests					
Johnson *et al.* (1998)	Beech-cherry-maple; Appalachian hardwoods; mixed oaks	March–June		58	–	28	Only bole damage assessed
		July–October November–February		46 34	– –	23 14	Only bole damage assessed

[a]The proportion of wounded trees is given. If the study distinguished between pole- and saw-timber wounding, this is shown. In cases where a size-based analysis was not conducted, the overall wound percent is shown, the number appears in the centre column
[b]In cases where severe wounds were defined by another measure, that measure is given in the table cell
[c]The clearcut treatment in which shortleaf pine residuals were left as residuals and surveyed, is not included here
[d]Treatment codes: RBA=residual basal area; DL=diameter limit; CC=clearcut; BAR=basal area retention
[e]Only dominant and co-dominant trees included in wound severity percentages are shown
[f]Crown damage in this study consisted of trees bent over or having broken stems owing to harvest operations
[g]This was termed a "shelterwood cut" but the author indicates the trees were marked incorrectly thus it is characterized as RBA of 40 partial harvest

returned mixed results in considering residual basal area and associated stand damage levels. Nyland (1986) suggested that "*The incidence of damage seems to increase with the intensity of thinning operation*." Consequently, residual stand damage may be more likely related to thinning intensity defined as the proportion of residual basal area to initial stand basal area.

Smaller poletimber and sapling-sized trees are more frequently wounded in harvesting operations (Table 2). Sapling-size trees (<5 in; 12.7 cm), often in abundance in the understory and not yet identified as future crop trees, are damaged significantly in all types of harvest operations with often suffering broken tops (Miller *et al.* 1984, Lamson *et al.* 1985, Nyland 1986, Fajvan *et al.* 2002, Dwyer *et al.* 2004), but typically with minimal effect on short- and mid-term stand value.

Felling and skidding as causes of stem wounding

The type of skidding equipment used and the length of the logs being yarded affect the amounts of damage sustained by residual trees. Track and rubber-tired skidders pulling log- and tree-length sections were compared in a northern hardwood forest (Meyer *et al.* 1966). The percentage of the residual stands sawtimber and pole-sized trees damaged was just over 2% when log-length sections were skidded (no difference between track and wheeled vehicle damage rates). Bole damage to residual sawtimber stems and pole-sized stems rose by 1 and 4.5 percentage points, respectively, when tree-length logs were skidded (Meyer *et al.* 1966).

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 *et al.* (1994). This was true for an operation utilizing manual felling and a conventional rubber-tired skidder compared to a mechanical harvest utilizing a feller-buncher. The probability of wounding of trees located adjacent to skid trails averaged 40% and 60% for the conventional and mechanical operations, respectively. However, damage to stems in the mechanical harvest rapidly decreased with as distance increased with only about 3% of residual stems damaged at 18 ft. [5.5 m] from the skid trails. Damage from the conventional operation drops more gradually with increased distance with an estimated 15% of stems damaged at 18 ft. [5.5 m] from the skid trails (Nichols *et al.* 1994).

Damage caused by tree felling only was assessed by Miller *et al.* (1984) for three thinning levels applied to central Appalachian mixed oak-cove stands. Overall, between 26 and 34% of the residual stems were bent, leaning, or destroyed in the three thinning treatments by tree felling. However, less than 3% of the residual crop trees (≥ 11″ [27.9 cm] dbh) were affected. Between 13 and 25% of residual stems had bole injuries that exposed sapwood, but for crop trees the incidence was less than 6%. Broken tops that occur when a falling tree hits the upper bole of a residual tree were tallied for between 21 and 30% of residual stems but the larger residual stems had broken tops post-harvest only rarely—less than 2% incidence rate.

The impact that skidding has on residual tree damage as compared to felling is distinctly defined in the work of Bruhn *et al.* (2002) based on an extensive evaluation of harvest operations in the Missouri Ozark Forest Ecosystem Study. Overall, across both even-aged and uneven-aged treatments, 74% of injured crop trees (≥ 10″ [25.4 cm] dbh) were located within 6 ft. [1.8 m] of skid trails. One out of every two crop trees proximal to primary skid trails suffered stem injuries (Bruhn *et al.* 2002). In a study based on 33 non-controlled harvesting operations in West Virginia (Egan and Baumgras 2003), 13% of residual pole and sawtimber stems were damaged with 62% of the damage occurring during skidding and 38% resulting from tree felling.

Season of harvest

Trees harvested in the spring and early summer are at greater risk of suffering harvesting-induced damage and future degradation through increased exposure of sapwood from mechanical abrasion and an increased proportion of trees with large wounds (Johnson *et al.* 1998). At a single location in Maine, harvesting resulted in the wounding of 35% of residual trees in the summer harvest compared to 18% for the winter harvest (Nichols *et al.* 1994). The wound width to tree circumference ratio indicated larger wounds resulting from summer (39%) than winter (25%) harvests. A multiple location study in West Virginia provides more robust evidence of this effect with a 24 percentage-point difference in the proportion of trees wounded in spring harvest operations (58%) compared to winter harvest operations (34%) (Johnson *et al.* 1998). Larger wounds (> 100 in^2 [650 cm^2]) also were significantly more prevalent after spring harvesting as compared to winter harvesting (Table 2).

Wound location and size

Wounds to tree boles versus tree crowns and roots result in different impacts on wood quality and tree function. Also, the types of pathogens that the tree sections are exposed to can be different. Most of the harvest and wounding studies had as their primary goal identifying, quantifying, and characterizing bole wounds with little attention given to crown and/or root damage (Table 2).

Three studies focused on distinguishing among wounds that affected all three sections of trees: stem, roots, and crown. Meadows (1993), Hassler *et al.* (1999), and Dwyer *et al.* (2004) recorded bole wound frequency from 46 to 91%, crown damage of 4 to 18%, and root damage of 2 to 50%. The approaches taken for determining root damage were very different among these studies. Many other operational, stand, and sample characteristics varied as well. Hassler *et al.* (1999) analysis of a post-harvest survey of logging jobs throughout West Virginia is likely representative of the frequency of occurrence of the different types of logging damage for typical harvest operations in the Appalachian region (Table 2).

Bole wound size is an important determinant of the probability a tree will recover without significant wood discoloration and decay. Wound size is frequently recorded as the maximum height multiplied by the maximum width of the area of exposed wood. Nyland and Gabriel (1971) presented several criteria to evaluate the potential seriousness of wounds. Bole wounds with abraded bark "*that remove bark from at least 150 in^2 [975 cm^2] of trunk surface have a 50% chance of developing decay within 10 years*" (Nyland 1986). Subsequent studies have usually used the threshold of Hesterberg (1957), 645 cm^2 [100 in^2], to identify bole wounds that are severe enough to have a significant probability of further degrading due to decay over time. The overall mean percentage of residual trees having serious wounds, as defined by Hesterberg (1957), for the 14 studies summarized in Table 2 is 16%.

Wounding from prescribed fire

Localized heating from prescribed fire can also wound trees depending on fire conditions and constitutive protective features of the tree such as thick bark. Most of the studies on the effects of prescribed fire in the eastern hardwood forests of North America have focused on oak regeneration with little consideration of the impacts on residual sawtimber. Some studies sought to determine the effect of fire on the survival of residual stems as small as 12.7 cm [5 in] dbh. Some of these studies reported survival results for "overstory" vs. "all" residual trees. Others present best-fit linear regression relationships of tree survival/mortality to DBH. A handful of studies looked at the influence of prescribed fire on hardwood tree mortality. Another set of studies targeted questions related to the impacts of prescribed fire on residual stand structure and species dynamics. Notably, fire research prior to 1960 almost exclusively focused on wildfire impacts on overstory trees (Brose *et al.* 2014) which may best relate to prescribed fire effects on crop trees.

Unlike logging wounds, fire-caused wounds are difficult to tally soon after the fire has occurred. What can be tallied in the first months after a fire is the height and width (or circumference) of the bark area that has been burned, charred, or scorched. The evidence of some degree of heating or combustion of the bark does not indicate that any vascular cambium cells were killed or that a scar will develop (Smith and Sutherland 1999, Stambaugh *et al.* 2017); the sloughing of bark to reveal a cambial injury and scar may take several years after the fire. Alternatively, wound occurrence and size can be assessed through bole dissection of sample trees with external evidence of potentially lethal heating (Dujesiefken *et al.* 2005, Smith and Sutherland 2006). Bole dissection studies contribute much information to our understanding of tree response to heat-caused injury, wound closure rates, decay occurrence associated with wounds, and fire history but do not provide information on the rate or frequency of occurrence of fire wounding.

A small number of studies of prescribed fire have estimated the incidence of stem damage from prescribed fire in eastern hardwood stands (Table 3). For some of these studies, data figures and tables in publications either presented, or allowed for the calculation of the damage specific to overstory trees as separate from all tallied stems (minimum sizes varied among studies). The number of cells in Table 3 that are empty is an indication of the variability of these studies. As observed related to logging damage studies, among study differences is the way damage/scarring is defined and the minimum tree sizes measured (generally minimum sizes were in the 2 to 5 in [5.1 to 12.7 cm] range). Differences in fire temperatures, stand basal areas, topography, etc. are not at all captured by this simple summary table. With consideration of these caveats, the overall mean proportion of trees damaged in the seven studies included in Table 3 is 41% with damage proportions ranging from 21% to 66%.

Wounding rates and severity associated with prescribed fires

Forest landowners and managers consider the effects of prescribed fire on the economic return from future harvests. Those effects include the potential for tree mortality and reduced yield of high-quality products due to reductions in grade (Tables 2 and 3). The extent of mortality and wounding is determined by fire intensity and duration. Unfortunately, wound sizes are largely missing for the prescribed fire studies that provide wounding rate results. The position of the wound on the tree (root, tree base, bole, and top or crown) is also critical. This information was collected in some of the logging studies summarized in Table 2, but not in the prescribed fire studies summarized in Table 3. Wound types and sizes measured in prescribed fire research are available from other studies that only focused on wounded stems (Guyette and Stambaugh 2004, Stambaugh and Guyette 2008).

Differences among species in overstory tree susceptibility to wounding caused by prescribed fire are attributable, in large part, to the level of protection offered by the bark. Bark thickness is the key protective factor, but heat transmission through bark of equivalent thickness can vary between species (Spalt and Reifsnyder 1962, Hengst and Dawson 1994) as does the rate of bark regrowth. The component of bark thickness that has been identified as particularly important is the thickness of the phellem or outer, corky layer (Stickel 1941). The thickness and low density of the outer bark provides most of the insulation from fire ascribed to bark (Hare 1961). Several North American hardwoods such as chestnut oak have thick bark that contains deep longitudinal fissures between the bark ridges or plates. Scarring can occur beneath those fissures where the thinner bark is not as protective (Sutherland and Smith 2000, Smith and Sutherland 2001).

The rate at which bark thickens as a tree matures and increases in girth (DBH) varies by species. This rate was modeled for 16 species common in the Central Hardwood Region in the U.S. by Hengst and Dawson (1994) with 15 of the 16 models having r^2 values above 0.55 (the sweetgum model performed poorly). Chinkapin oak (*Quercus muehlenbergii* Engelm.), red oak (*Quercus rubra* L.), shingle oak (*Quercus imbricaria* Michx.), American sycamore (*Platanus occidentalis* L.), and silver maple (*Acer saccharinum* L.) were determined to have the lowest rates of bark thickening of the 15 species with well-performing linear models. Cottonwood (*Populus deltoides* Bartr. ex Marsh.), black walnut (*Juglans nigra* L.), bur oak (*Quercus macrocarpa* Michx.), yellow-poplar (*Liriodendron tulipifera* L.), and white pine (*Pinus strobus* L.) were the five species with the greatest rates of bark thickening with increasing tree DBH (Hengst and Dawson 1994). Overall, the Hengst and Dawson results indicate that upland hardwood species produce thicker bark at a younger age than do lowland hardwood species.

That the characteristically thinner bark of younger trees leads to high fire-caused mortality for these stems is well known, but Keyser *et al.* (1996) identified a notable species-based difference in sapling mortality. The Keyser study indicated that oak reproduction (oak species not specified) was not killed to the same extent as red maple and yellow-poplar by prescribed fire applied during the summer. This result prompted similar studies which confirmed that white oak seedling and saplings were more fire-resilient than seedlings of associated species (Brose *et al.* 2014).

One of the first North American studies of eastern hardwood tree species response to fire was conducted by Nelson *et al.* (1933). Their study of fire wounds 1-year after a severe wildfire near the Blue Ridge Parkway in west-central Virginia, indicated important species differences in wound size. The

Table 3. Prescribed fire caused wounding of hardwood stems

Study authors and year	Location	Forest type	N	Prescribed fire treatment	Mortality proportion		Damaged/scarred proportion		Mean scar width (cm) or circum. (%)	Mean scar height (cm)
					Over-story	All	Over-story	All		
Wendel and Smith (1986)	Central Appalachia	Oak-hickory	2415	Spring	5%	–	66%	–	–	162.6 ± 27.9
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 *et al.* (2008)	MO	Ozark uplands: oak-hickory-shortleaf pine	3754	Southwest facing slopes	–	–	–	64%	r. oak: 27.9 b. oak: 27.9 w. oak: 22.9	88.9 78.7 78.7
				Northeast facing slopes	–	–	–	52%	post oak: 20.3 Carya sp: 17.8	61.0 61.0
Ward and Brose (2006)	CT	Eastern oak	3476	7 Rx fires	–	–	Oak: 25%	–	–	–
							Non-oak: 28%	–	–	–
Wiedenbeck *et al.* (2016)	WV	Mesic upland hardwoods	1777	Shelterwood-burn - 2 spring fires	–	9%	–	33%[a]	–	–

[a]Char percentage was 60% immediately after the fire

researchers found that yellow-poplar was distinctly more resistant to wounding by fire than scarlet oak when considering larger diameter trees. This study also examined the relationship between tree diameter and the size of fire wounds for three of the species, providing early substantiation of the greater vulnerability of younger, smaller-diameter trees have to fire wounding than older, larger-diameter trees of the same species.

Estimates of the likely impact of a fire on crop tree mortality and quality soon after the occurrence of the fire have been based on the degree of bark scorch. Unfortunately the relationship of scorch to cambial injury is variable and can take two or more years for cambial death and the induction of scar formation to become evident (Smith and Sutherland 1999). This variability is evident in Loomis (1973), an oft-cited study that modeled mortality and wound size based on bark scorch measurements of trees in 28 burned stands in Missouri, Pennsylvania, and West Virginia. He predicted that the height and width of expected wounds for red oak, black oak, ash, hickory, and scarlet oak would be 90% and 60%, respectively, of the height and width of bark blackening measured in the months following a dormant season fire. For white oak, post oak, and chestnut oak, he found the height of the wound that would eventually appear would only be about 70% of the height of the blackened bark. The wound width relationship for these oaks was the same as for the other species group.

Species differences in the probability of being injured by fire also were explored in an upland Missouri Ozark forest by Stevenson *et al.* (2008). They concluded the species-based risk of wounding from fire was: "red oaks > black oak = white oak > post oak = hickories > shortleaf pine." The height of char (defined by Loomis (1973) as a more severe form of bark blackening than scorch) on the tree bole was determined to be a weak to moderate predictor of scar/wound height for all of the species groups (Stevenson *et al.* 2008). These two studies provide further evidence that species in the white oak subgenus are more fire tolerant than species in the red oak subgenus, however neither study included the commercially important thinner-barked eastern hardwood species: sugar maple, red maple, and black cherry.

Vulnerability to fire and logging injury

Vulnerability to injury or mortality from a given level of fire exposure (temperature and duration) is largely governed by bark thickness and thermal properties. Thermal properties of tree boles vary among species and may be affected by the moisture content, specific gravity, and thermal diffusivity of the bark. Bark properties thought to influence thermal properties have been examined for few species under limited temperature and moisture content conditions (Butler and Dickinson 2010). Repeatedly, the conclusion derived from studies of bark properties and heat-caused injury is that bark thickness is the best predictor of a tree's ability to resist cambial injury from fire (e.g., Hengst and Dawson 1993, Schoonenberg *et al.* 2003, Dickinson and Johnson 2004).

Thicker bark would also likely protect the vascular cambium from some sources of logging injury. However, bark protection from direct impact from a falling stem or from harvesting equipment would be expected to increase with greater impact strength and higher bark density. In addition to resistance from simple impact, felling injury also results from shear stress as the falling tree abrades an adjacent standing tree on its way to the ground. Even when the outer bark remains intact, it can be stripped off of the stem due to structural weakness within s or between the component tissue layers: rhytidome, phloem (inner bark), the vascular cambium, developing xylem, and fully differentiated wood. Further, the tendency for species with thinner bark to have higher specific gravity than thicker-barked species (Hengst and Dawson 1993), is a factor since wood with higher specific gravity has higher thermal conductivity (Steinhagen 1997). Insight into stem abrasion caused by tree felling may be found in research on the mechanical debarking of logs for hardwood products. Einsparh *et al.* (1984) found no differences among hardwood species in the adherence of bark to wood in logs felled during the growing season. For those logs, the bark separated from the underlying wood in the cambial layer or in the newly formed xylem. For trees felled during the dormant season, bark separated to the outside of the cambium at the inner bark or phloem. Einsparh *et al.* (1984) interpreted these findings as indicating that the strength of the inner bark and the toughness of the wood were the primary factors affecting the adhesion of bark to the underlying wood during the dormant season. Out of 24 hardwoods tested, shagbark hickory, white ash, black oak, northern black cottonwood, and black willow held their bark most strongly during the dormant season. Southern white oak, northern white oak, southern red oak, northern red oak, and American beech had the lowest resistance to bark sloughing.

Anatomical research on the phenology of phloem differentiation and cell division of the vascular cambium on trees across the temperate zone show seasonal increases in the width of the vascular cambium during the growing season (e.g., Smith *et al.* 1984, Prislan *et al.* 2013). In winter dormancy, the cells of the vascular cambium are few in number and narrow along the stem radius (Larson 1994). Under these conditions, the bark will tend to adhere more strongly to the stem. During the growing season, the number of vascular cambial cells and undifferentiated daughter cells increase in number as cell division proceeds, providing a structural weakness and vulnerability to abrasion. This vulnerability is the basis for the traditional recommendation to avoid forestry operations early in the growing season that could wound stems. Oak species known for having bark that is effective in insulating the underlying wood from the heat of fire appear to be less protective when mechanical forces are applied that peal the bark from the wood (Einspahr *et al.* 1984).

Smith and Sutherland (1999) dissected and analyzed tree scars on the lower bole of oaks in southern Ohio and concluded that the appearance of historical wounds is not distinctly different for trees injured by fire as opposed 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.

Studies have identified a difference in tree response to wounding depending on the season in which the wounding occurs. A controlled wounding study by Dujesiefken *et al.* (2005) showed that dormant season wounding results in longer columns of discoloured wood—3 to 4 times longer than when wounding occurs in late winter and spring—and slower wound closure rates. Wounds inflicted in April resulted in faster rates of wound closure and shorter columns of discoloured wood than wounds incurred in February, October, and December (Dujesiefken *et al.* 2005). The authors concluded that tree pruning should not be performed during the dormant season. Thus, while trees may be more susceptible to wounding in the spring when the adhesion of bark to wood is weaker, the higher levels of metabolic activity that occur during the growing season may allow spring-wounded trees to respond more quickly and effectively to minimize damage.

Closure of fire scars

How quickly a species is able to close an open wound after fire injury (Stambaugh *et al.* 2017) is a related factor that influences the vulnerability of trees to further wounding. The wood exposed by the sloughing of killed bark becomes more vulnerable to charring in successive fires. The thin, young bark on the woundwood ribs (Fig. 1) provides less protection to the vascular cambium than well-developed outer bark or rhytidome. When wound closure is complete, the circumferential continuity of the vascular cambium is restored. Closure also tends to slow wood decay through the reduction of oxygen availability to the wood decay fungus. For forest managers using prescribed fires to promote oak regeneration, the application of more than one prescribed fire to achieve a silvicultural objective means that wound closure rates for midstory and overstory trees are particularly important.

Trees with faster radial growth are able to close wounds more quickly than slow-growth species. Wounds that are wider require longer to close than do narrower wounds. Sections of wounds that are narrower, for example, the top point on a triangular-shaped wound that starts at the base of the bole, (sometimes referred to as a catface), closes quickly while the widest part of the same wound can take years longer to be covered. As an example, bole wounds in sugar maple have a 50% chance of developing decay after 10 years if the wound size is greater than 150 in^2 [975 cm^2] and an 80% chance of developing decay for wounds that exceed 250 in^2 [1625 cm^2] (Hesterberg 1957). The bark that covers wounds will be thinner than surrounding bark for many years, thus not affording as much heat insulation and protection from mechanical damage.

Observational studies of wound closure rates based on periodic revisiting of injured stems were conducted by Smith *et al.* (1994) and Jensen and Kabrick (2014). In both studies, the wounds were caused by logging activities. Smith *et al.* (1994) collected wound re-measurement data five and ten years after wound initiation on 99 bole wounds on 70 to 80 year-old residual crop trees. Northern red oak, white oak, and yellow-poplar comprised the majority of their sample; for these three species, just less than half of the wounds with initial exposed wood areas ≤100 in^2 [650 cm^2] had closed after five years. No wound closure was recorded for any of the larger wounds. After ten years, 88% of the smaller wounds had been covered by woundwood but only 19% of the larger wounds were closed (Smith *et al.* 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 in [11.43 cm] DBH and larger. Wound sizes were not reported but overall, 76% of the wounded trees no longer had open bole wounds. Their sample size was large—938 trees, so species-based differences in wound closure proportions were explored and found to be significant, with white oak (92%), scarlet oak (82%), black oak (58%), hickories (36%), and shortleaf pine (17%) being the most to least successful in closing wounds after 13 years. While both crown position and size class can be related to vigour and radial growth increment, they did not find either factor significant in predicting wound closure. For all tree species and wound sizes combined in the Smith *et al.* (1994) study, 59% of bole wounds were closed after 10 years compared to 76% closed after 13 years in the Jensen and Kabrick (2014) study. With the diversity of insects and pathogens that exist in eastern hardwood forests, wounds open for multiple years are subject to becoming infection courts to decay as described by Berry (1969, 1977) and Berry and Beaton (1972).

More precise estimates of the rate of wound closure can be obtained using tree dissection and dendrochronological inspection techniques. This approach was used by Stambaugh *et al.* (2017) to determine the rate of wound closure of fire scars on white oak growing in Missouri. Based on analysis of 56 wounds, the linear relationship between wound size ("scar arc length") and years to wound closure was modeled with an r^2 of 0.54. They determined a mean fir scar closure rate for their white oak sample of 1.32 cm/yr. As other studies in Missouri showed white oak to be the species that was most effective at closing wounds after 13 years (Jensen and Kabrick 2014), closure rates for other species are expected to be slower.

Quality, grade, and value impacts from wounds

Several studies have been conducted to 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. Increased use of prescribed fire, often on a recurring basis and sometimes in combination with shelterwood establishment cuts, indicates the importance of managing forests with knowledge of wound closure rates and impacts on merchantable tree volume and wood quality where economic yield is a high priority.

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. Logs with wounds suffered a mean value loss of 11% when evaluated 10 years after wounding with 9% of the sample logs reduced in grade owing to wound associated degradation of the log. However, the mean value loss of the lumber sawn from these logs was only 3%. In another recovery study of sugar maple (Ohman 1970), value losses associated with wounds from harvest operations were even lower after 10 years, 1% for logs and 3% for lumber. Yellow birch recovery was evaluated in the same study and reported a 12% log value loss and 4% loss in lumber value.

Estimated log grade impacts for the butt logs of residual trees were substantially higher in a study conducted in the southern Appalachians in which basal area retention treatments were varied (Clatterbuck 2006). For all treatments combined, 45% of the trees with damaged boles dropped in log grade. A similar approach was taken by Johnson *et al.* (1998) in a broader scale study in the central Appalachian region with 20 shelterwood with reserves stands evaluated for butt log grade changes in the residual trees that were attributable to logging damage. The results were much more in line with those of Hesterberg (1957) and Ohman (1970) with less than 2% of the butt logs losing grade two to five years after completion of logging operations. The Clatterbuck (2006) results should be looked at as "worst case" results as indicated by observations made by the author regarding the mistakes made by the logger. With Clatterbuck (2006) and Johnson *et al.* (1998) assessments conducted only two to five years after wound occurrence and the fact that the valuation was performed on standing timber rather than on actual logs, (in which case the log ends would be visible for evaluation as well), it is expected that further degradation owing to decay development associated with some of the wounds would lead to further value loss over time.

An important study of fire impacts on wood quality and value (Loomis 1973, 1974) was based on the effects of wildfires. Applicable to oak-hickory forest types, the value loss was estimated for a wide range of tree sizes and fire intensities. Value and volume losses were modelled based on wound age, height, and width, and tree diameter at the time of the fire. The equations explained approximately half the variation in lumber value and volume loss. Loomis (1989) composed a look-up table for estimated volume loss due to basal fire wounds based on his earlier research. The factors needed to use the table are DBH, wound height, wound width, and the number of years since the fire occurred.

Wildfire-caused stumpage value losses for entire hardwoods stands informs the discussion of prescribed fire use near the end of rotation in oak-hickory forest types. Reeves and Stringer (2011) determined, based on 10 sets of matched burned and unburned stands, that the timber value loss from wildfires ranged from 5% to 65% with an average loss of 47%. Of the estimated loss, 28% was attributed to cull volume related to fire-caused wounds while 72% was related to structural changes including tree mortality and changes in species and size classes of timber. A more coarse approach was taken by Wood (2010) to assess the value loss to crop trees in stands allocated within a West Virginia state forest that had experienced zero to six wildfires over several decades. Tree value losses increased with increasing fire exposure levels, ranging from a 10% decline in crop tree sawtimber value for stands subject to one wildfire to 53% for stands surviving six wildfires. The corresponding declines in sawtimber volumes ranged from 6% to 55%. The stand value effects determined by Reeves and Stringer (2011) and Wood (2010) align well with each other with value losses ranging from 5% to 65% in the former study and from 6% to 55% in the latter.

Prescribed fire impacts on the quality and value of the residual crop trees in a timber stand have received minimal attention. Known studies to date have been conducted on oaks in Missouri (Stambaugh and Guyette 2008, Marschall *et al.* 2014, Knapp *et al.* 2017). The other reports on this topic were conducted at a single site in West Virginia at which a shelterwood-burn study was being conducted. These provide insights on tree quality (Wiedenbeck *et al.* 2017) and product value (Wiedenbeck and Schuler 2014) effects of prescribed fire on central hardwood species. The dearth of information related to effects of prescribed fire, together with the increased use of prescribed fire in eastern hardwoods to address oak regeneration and forest restoration objectives, has led to significant new research activities focused on this subject (Stanis and Saunders *In press*).

Analysis of 41 basal tree sections containing fire scars caused by a prescribed fire that occurred six years earlier provided averages for scar size (41 cm^2), woundwood volume (24 cm^3), decay volume (27 cm^3) and discoloured wood volume (27 cm^3) for a sample of white, black, and scarlet oak stems (Stambaugh and Guyette 2008). Of the butt logs from fire scarred trees dissected in this study, 20% dropped in grade due to the fire injury suffered six years earlier. Tree and lumber volume and value loss estimates for 88 red, black, and scarlet oak trees were measured by Marschall *et al.* (2014). Many of the butt logs from these trees showed scars indicating they had been exposed to more than one fire, including more recent scars of prescribed fire origin and older scars of wildfire origin. The average lumber volume and value losses per tree were 4% and 10%, respectively, with many boards dropping in lumber grade but not in volume.

Isolating the effects of a single fire on a stem that has been through a series of fires can be difficult because the tree response to injury and the development of discoloured and decayed wood from one event often merges with regions affected by previous events. Isolating the wood quality changes attributable to two prescribed fires that were conducted five and eight years prior to harvest indicated only minor effects of prescribed fire on lumber quality with about 16%, 13%, 12%, and 7% of the lumber recovered showing any signs of fire damage for red maple, red oak, white oak, and yellow-poplar, respectively (Wiedenbeck and Schuler 2014). Visible lumber indications noted were minor in almost all cases—a short streak of mineral stain (red maple in particular), minor surface checking (red and white oak), and small areas of incipient decay. Recent low intensity fire exposure appears to have very little impact on the quality, and therefore value, of hardwood lumber recovered from affected stems, but studies to-date have been limited in number and scope.

The effects of prescribed fire on residual stand value, as opposed to the value of individual merchantable stems, has been given even less attention. Stand value losses for areas in Missouri that had a history of multiple periodic prescribed fires were estimated to be less than 3% (Knapp *et al.* 2017). They did however, find that the total stumpage value of these stands was 30% lower than the stumpage value of unburned stands. The former of these value decline figures is based only on losses to existing merchantable stems (i.e., cull volume) while the latter includes structural changes in the stands such as shifts in tree species and size. This result matches with the results and conclusions of Reeves and Stringer (2011) in their study of wildfire impacts on stand value. Unfortunately, Knapp *et al.* (2017) work was limited to red oak forests in Missouri.

Conclusions

The economic value of hardwood products varies by tree species, size, and current market conditions and is strongly affected by the quality of the wood that can recovered from the tree. The presence of wound-initiated wood discoloration (stain) and decay reduces the potential yield of high-value products. Hardwood management activities including mechanized stand entries for harvesting and thinning as well as prescribed fire can wound trees and increase cull volume. The relationship between tree wounding and product degrade depends on wound severity and frequency, growth rate after injury, and the process of wound compartmentalization and closure. While regional surveys of the residual tree injury rates post harvesting have been conducted, similar broad assessments of fire-caused injury rates, severity, and recovery over time do not exist. Having this information would help forest managers make decisions on prescribed fire application and wildfire salvage response.

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