Damage to trees due to forestry operations and its pathological significance in temperate forests: a literature review

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Summary

The damage caused to temperate forests by forestry operations is examined by a review of the scientific literature. A significant proportion of the remaining trees, especially in older stands, can be damaged during mechanized selective logging in forests, when operations are carried out in summer. Damage is most often caused during transport of timber. Most of the resulting wounds occur near the base of the tree and are up to 200 cm^2 in size. Damage to roots has negative effects on tree growth. Wounds on trees are attacked by fungi, causing stain and decay. In most tree species, the spread of wound decay is extensive and devalues several metres of the butt log. Wound closure is usually too slow to have any significant effect on the incidence of wound infections, but in several tree species it may restrict the spread of decay. The financial losses in wood value at the final harvest, due to previous logging damage, are reported to be significant. Strategies are discussed for controlling the damage and wound decay in a forest, emphasizing silvicultural options for care of a stand during selective harvesting and wound treatment with appropriate dressings.

Introduction

From the beginning of the twentieth century, the increasing use of mechanized wood harvesting brought with it the problem of damage to the remaining trees in forest stands. Westweld (1926) was among the first to point out the significance of injury to coniferous reproduction due to logging operations. He was followed by Perry (1929), who studied the survival of pine regeneration following various logging methods. Consequently, a number of suggestions were made for reducing damage caused by tractor skidding in pine forests (Wales, 1929). An early study in hardwood stands also indicated that logging injury to trees was unacceptably common, leading to serious economic losses (Kuenzel and Sutton, 1937).

Following the widespread introduction of mechanized harvesting into practical forestry after World War II, the problem of damage to the remaining growing stock increased, especially in the industrialized countries within the northern coniferous zone (Lang, 1980; Kallio, 1984; Melekhov, 1986). Since the damage in intensively managed forest stands is usually in the form of wounds to the remaining growing stock, this enhances the spread of wound pathogens into living trees and wound decay formation, which may seriously affect quality of timber at the final harvest (Shigo, 1966; Pechmann, 1974; Dimitri, 1983). The present paper aims, by means of a literature review, to address the following questions: (1) what proportion of the remaining trees in forest stands are damaged during various logging operations? (2) what are the patterns, size and distribution of the wounds inflicted? (3) how often are wounds on trees attacked by fungi, causing stain and decay? (4) how extensive is the spread of wound decay in individual stems? (5) what are the losses in wood value at the final harvest of a damaged stand? (6) what methods exist for controlling wounding and wound decay in a forest?

Extent of the damage

Not all tree species are equally susceptible to mechanical injury. In both Europe and North America, pines are regarded as relatively resistant to such damage, whereas spruce are among the most sensitive (Pawsey, 1971; Froehlich, 1976; Cervinkova, 1980; Dimitri, 1983). Table 1 summarizes the data regarding the extent of damage caused to the remaining growing stock following various logging operations in temperate forests. It is obvious that in intensively managed forest stands injury to the growing stock due to forest operations may take place throughout the rotation period. For example, 8–11 per cent of trees had already been damaged during mechanized clearing in 7–16-year-old plantations of Norway spruce. In commercial thinnings, wounding of the residual trees is, in practice, unavoidable. A number of studies in conifer and mixed stands have shown that mechanical injury resulting from thinnings was found on 4–21 per cent of the remaining trees. On the other hand, thinnings when <4 per cent of the remaining trees are damaged should not be regarded as exceptional cases. During partial and shelterwood cuttings in older stands, the larger trunks are removed and the number of injuries is usually higher than during thinnings. Also the larger and more powerful machines were reported to cause more extensive damage (Pawsey and Gladman, 1965; Šakúnas, 1975). A frequency of damage ranging between 5 and 15 per cent of the remaining trees should therefore be regarded as low. In regions where shelterwood and selective forestry has a long history, as for example in Germany or Austria, the incidence of trees wounded by logging can accumulate up to 47–72 per cent of the stems towards maturity in spruce stands (Schimitschek, 1975). Also, in the conifer stands of North America, up to 40–60 per cent of the remaining trees showed various types of mechanical injury following partial cuttings. At the final harvesting phase of a mature stand, considerable damage can be caused to the next forest generation. In Lithuania and Russia it was noted that between 7 and 30 per cent of young spruce regrowth emerging on clear-cut sites had injuries.

Wounding patterns, size and distribution

Damage to the residual stand in forest operations is most often caused during transport of timber (Shea, 1960; Hunt and Krueger, 1962; Hasek, 1965; Kärkkäinen, 1969; Pawsey, 1971; Huse, 1978; Krayev and Valyaev, 1980; Vasiliauskas, 1993). Trees are wounded by machines and logs under extraction (Hannelius and Lillandt, 1970; Siren, 1981, 1982; Grinchenko, 1984). Most of the resulting wounds occur at or near the base of a tree (Shea, 1960; Froehlich, 1976; Kazemaks and Peilane, 1977; Vasiliauskas and Pimpe, 1978; Siren 1981, 1982; Bettinger and Kellogg, 1993; Kovbasa, 1996). In spruce stands harvested by partial and shelterwood cuttings, only 15 per cent of all tree wounds were situated higher than 0.5 m, and over 60 per cent of the trees were damaged at the root collar, i.e. 0.3 m height from the ground (Vasiliauskas, 1993). When tractors equipped with a boom were used for harvesting, 90 per cent of the damage to the remaining trees was below 1.5 m height on the stem (Athanassiadis, 1997). Of all wounds caused to spruce due to thinning operations, 39 per cent were root wounds, 26 per cent root collar wounds, and 35 per cent stem wounds (Huse, 1978).

In conifer stands in Finland, damage caused by machines to trees during thinnings in 35–56 per cent of cases consisted of superficial wounds where the bark was removed, and in 20–52 per cent of cases it resulted also in breakage of the

Table 1: Amount of damaged trees in temperate forests due to forestry operations

Tree species	Stand age (years)	Geographical location	Damaged trees left growing (%)	Source
Precommercial thinning				
Picea abies (L.) Karst.	6–14	Central Sweden	8–11	Wästerlund, 1988
Pinus contorta Dougl.	10	Central Sweden	16	Wästerlund, 1988
Commercial thinning				
P. abies	31–54	Scotland	2	El Atta and Hayes, 1987
P. abies	30–60	Russia	4	Georgievsky, 1957
P. abies	30	South Sweden	6	Athanassiadis, 1997
P. abies	20–45	Byelorussia	5–16	Kovbasa, 1996
P. abies	40–60	South Germany	13–16	Aufsess, 1978
P. abies	40–50	South Norway	13–21	Huse, 1978
P. abies	50–60	Lithuania	7–28	Vasiliauskas, 1998b
P. abies	50–65	England	20–46	Pawsey, 1971
Pinus sylvestris L.	20–70	Ukraine	2–21	Grinchenko, 1984
P. abies, *P. sylvestris*	30–40	Latvia	1–4	Kazemaks and Peilane, 1977
P. abies, *P. sylvestris*	20–41	Finland	2	Siren, 1981
P. abies, *P. sylvestris*	–*	Sweden	3	Eriksson, 1981
P. abies, *P. sylvestris*	–	South Finland	2–8	Hannelius and Lillandt, 1970
P. abies, *P. sylvestris*	40–60	Finland	6–22	Siren, 1982
P.abies, *Populus tremula* L.	30–40	North Russia	4–13	Sokolov and Schedrova, 1973
P. abies, *Betula pendula* Roth.	30–60	Russia	10–13	Krayev and Valyaev, 1980
P. abies, *B. pendula*, *P. tremula*	30–60	Russia	10–14	Marchenko, 1964
Pseudotsuga menziesii (Mirb.) Fr.	37	North-west USA	11–12	Hunt and Krueger, 1962
Tsuga heterophylla (Raf.) Sarg.	47	North-west USA	33	Hunt and Krueger, 1962
Picea sitchensis Carr., *T. heterophylla*	45	USA, Alaska	10–15	Sidle and Laurent, 1986
P. menziesii, *T. heterophylla*	47	USA, Oregon	40	Bettinger and Kellogg, 1993
Betula papyrifera Marsh.	45	USA, Maine	49	Ostrofsky *et al.*, 1986
Quercus rubra L., *Fagus grandifolia* Ehr	–	USA, Maine	32	Ostrofsky *et al.*, 1986
Partial cutting				
P. abies, *B. pendula*, *P. tremula*	60–120	Lithuania	6–15	Šakúnas, 1975
P. abies, *B. pendula*, *P. tremula*	40–220	North Russia	6–11	Stolarov and Kuznecova, 1973
P. abies	80–100	North Russia	3–9	Muravyova, 1964
P. abies	70	Czech Republic	2–34	Soukup and Temmlova, 1977
P. abies	70–100	Lithuania	12–23	Vasiliauskas, 1989, 1993
P. abies	80–100	Austria	21	Steyrer, 1992
P. abies	90–120	Czech Republic	17–36	Hašek, 1965
P. abies	118	Czech Republic	52	Fanta, 1958
P. abies, *P. sylvestris*	90	South Sweden	7	Athanassiadis, 1997
T. heterophylla	100	North-west USA	59	Englerth and Isaac, 1944
Abies concolor (Gord.) Hildebr.	74	USA, Oregon	14–25	Aho and Filip, 1982
Mixed hardwoods	–	North-east USA	10	Cline *et al.*, 1991
Selective sanitation felling with <10% removal				
P. abies	85	Byelorussia	4–10	Kovbasa, 1996
P. abies	60–100	Lithuania	5–10	Vasiliauskas, 1989, 1993

Continued

Table 1: *Continued*

Tree species	Stand age (years)	Geographical location	Damaged trees left growing (%)	Source
Shelterwood cutting				
P. abies, *B. pendula*, *P. tremula*	60–90	Russia	5–7	Atrokhin, 1967
P. abies, *B. pendula*, *P. tremula*	60	Russia	7	Tikhonov, 1965
P. abies, *B. pendula*, *P. tremula*	60–90	Lithuania	6–16	Šakúnas, 1975
P. abies, *B. pendula*, *P. tremula*	50–60	North Russia	22	Muravyova, 1965
P. abies, *B. pendula*, *P. tremula*	50–70	Lithuania	28–46	Vasiliauskas, 1989, 1993
Regrowth on clearcut sites				
P. abies	10–20	Karelia	7–30	Schedrova, 1959
P. abies	10–20	Lithuania	18–28	Šakúnas, 1975
P. abies, *B. pendula*	10–20	Lithuania	22–30	Šakúnas *et al*., 1984

*–, not reported.

underlying wood. The proportions of broken roots and superficial bark scratches were 6–12 per cent and 3–12 per cent, respectively (Siren, 1981, 1982). In spruce stands in Lithuania, logging wounds were most common, where only the bark had been knocked off from the stem or roots, thus exposing sapwood, and only in 17 per cent of cases were deeper injuries recorded as damage to the wood layers (Vasiliauskas, 1993). These data correspond reasonably well with other studies in thinned stands, where the proportion of wounds with wood damage made up 16–23 per cent of all injuries (Hannelius and Lillandt, 1970; Eriksson, 1981; Sidle and Laurent, 1986). Other studies have also shown that most logging injuries do not penetrate the wood (Cline *et al*., 1991; Bettinger and Kellogg, 1993).

Logging wounds vary in size to a great extent. In North American conifers, scar sizes on damaged trees ranged from 0.13 to 2976.77 cm^2 (Bettinger and Kellogg, 1993). In another study only 5 per cent of all scars exceeded 30.5 cm^2 (Sidle and Laurent, 1986). On Norway spruce, logging wounds may reach 1000–3500 cm^2 in size (Aufsess, 1978; El Atta and Hayes, 1987; Vasiliauskas, 1993). However, a number of studies in spruce stands showed that most logging wounds are usually smaller than 100 cm^2 (Siren, 1981, 1982; Koch and Thongjiem, 1989; Vasiliauskas, 1993, 1998b; Athanassiadis, 1997), with an average size in the range of 50–200 cm^2 (Hannelius and Lillandt, 1970; Aufsess, 1978; Huse, 1978). However, in spruce stands in Byelorussia considerably larger wounds of 100–500 cm^2 surface area were most commonly recorded (Kovbasa, 1996). On young regrowth of spruce in clear-cut areas, the bark was knocked off 12–20 per cent of the stem perimeter (Schedrova, 1959).

Damage to roots and stems is less severe during forest operations carried out in winter, when the ground is frozen and bark is strongly attached to the sapwood (Hannelius and Lillandt, 1970; Kärkkäinen, 1969, 1973; Ohain, 1974; Grinchenko, 1984; Kallio, 1984). Winter injuries are usually smaller and less deep than those made in summer (Kärkkäinen, 1973; Isomäki and Kallio, 1974; Kovbasa, 1996).

Most trees wounded due to forest operations are not randomly distributed within a stand, but are situated close to the extraction racks (Marchenko, 1964; Huse, 1978; Bettinger and Kellogg, 1993; Kovbasa, 1996; Athanassiadis, 1997). Hannelius and Lillandt (1970) found 81 per cent of the injured trees close to the extraction racks, and in another Finnish study, Siren (1982) reported that only 10 per cent of wounded stems were >5 m from the centre of the extraction rack.

Effect of damage on tree growth

The results of several studies clearly indicate that growth losses occur in damaged trees, and in some cases these can seriously offset the gains from cuttings. About 65–85 per cent of tree roots are distributed throughout the upper soil horizons (Björkhem *et al.*, 1975). Subsoil root damage can decrease height growth of spruce by 25 per cent and radial growth by 35 per cent (Isomäki and Kallio, 1974). In spruce stands 14–25 per cent of the trees without visual damage showed a 25 per cent annual height growth reduction during the first 2 years after mechanized thinning due to soil compaction and to possible direct damage to the roots (Wästerlund, 1988). Root and soil damage after thinning operations could reduce the total volume production by 10–20 per cent (Björkhem *et al.*, 1974; Bredberg and Wästerlund, 1983; Wästerlund, 1989, 1992). Increment losses in spruce stands caused by tractor logging were estimated to be 5–15 m^3 ha^{-1} over 10 years (Kardell, 1978). In another Swedish study, the growth losses in a whole stand due to mechanized harvesting were approximately 4–5 per cent (Fries, 1976).

Wounding of tree stems during logging results only in partial girdling and therefore translocation within the tree is not completely interrupted. There are differing views as to whether mechanical damage to stems affects tree growth or not (Roeder and Knigge, 1972; Knigge, 1975). Some reduction in diameter growth was noted in injured Douglas fir (Shea, 1961). In Norway spruce trees, root collar damage following logging reduced both radial and height growth by 35–40 per cent, and trunk damage reduced growth by 15 per cent; width and depth of the injury correlated positively with the decrease in growth (Isomäki and Kallio, 1974). Several studies have showed that in spruce with stem wounds growth losses occur and can be as high as 14–25 per cent (Schimitschek, 1939; Baader, 1956; Vanek, 1957). In contrast, a number of investigations failed to reveal any significant effect of stem wounds on the increment of spruce (Heger *et al.*, 1955; Kräuter, 1964; Hilscher, 1964; Zaruba and Snajdr, 1966; Staines and Welch, 1984; Vasiliauskas, 1989), western hemlock (Shea, 1961) and oak (Vasiliauskas, 1998c). Following wounding, radial increment tended to increase in stems of ash (Vasiliauskas and Stenlid, 1998b). It is difficult, therefore, to make a general conclusion on what effect mechanical stem damage has on tree growth.

Incidence of stain and/or decay in wounds

The most important pathological consequence of mechanical damage to standing trees is development in wounds of stain or decay. It is known that discoloured wood does not always indicate that the wound has been entered by fungi. Cases have been reported where discoloration of wood in the wound vicinity was free of microorganisms, and such discoloration was considered a mechanism for potential protection of living trees against fungal attack (Pawsey and Gladman, 1965; Isomäki and Kallio, 1974; Aufsess, 1984).

With a few exceptions, the majority of tree species are reported to be very susceptible to wound infections (Table 2). Relatively low susceptibility to wound decay was noted for pines (Gorshin, 1935; Vasiliauskas and Pimpe, 1978), Douglas fir and several species of true firs. According to Aho (1960), logging scars on Pacific silver fir were not appreciably infected with decay fungi even after 9 years. Also in white firs (*Abies concolor* and *Abies grandis*), only a minority of wounds were entered by decay (Table 2). In contrast with the results obtained in many related studies, Pawsey and Gladman (1965) reported very low wound infection rates on Norway and Sitka spruces, and on Japanese larch. The average incidence of vigorous decay fungi in 3–20-year-old wounds was only 6.1 per cent. However, Pawsey and Gladman (1965) noted that many more scars were colonized by saprophytic organisms and decay fungi, which they regarded as minor. Solheim and Selås (1986), for example, found active decay fungi in 40 per cent of 2-year-old wounds on Norway spruce.

Variation in wound infection frequency could be attributed to several factors, such as differences in size and age of wounds, position of wound on a tree, or season of injury. It is known, for example, that larger and older wounds are more likely to be colonized by fungi (Vasiliauskas, 1998a, and references therein). Table 2 shows that, in general, 60–100 per cent of wounds inflicted to trees produce stain and/or decay. Therefore, where there is a high proportion of damaged trees in managed forest stands, wound decay fungi may form a significant part of the community of wood-inhabiting fungi. In spruce stands in Germany, the proportion of wound fungi among all fungi found in living trees was

Table 2: Incidence of discoloration and decay in 2-year-old and older open wounds of forest trees that are over 30 years of age

Tree species	Wounds entered by stain or decay (%)	Source
Picea abies (L.) Karst.	9	Pawsey and Gladman, 1965
P. abies	46	Roll-Hansen and Roll-Hansen, 1980
P. abies	47–54	El Atta and Hayes, 1987
P. abies	57	Solheim and Selås, 1987
P. abies	33–66	Schedrova, 1959
P. abies	58	Vasiliauskas *et al.*, 1996
P. abies	62	Muravyova, 1971
P. abies	57–82	Schönhar, 1975
P. abies	53–87	Vasiliauskas, 1989, 1993
P. abies	25–100	Kovbasa, 1996
P. abies	77	Vasiliauskas and Stenlid, 1998a
P. abies	60–93	Butin, 1980
P. abies	83	Bazzigher, 1973
P. abies	88	Domanski, 1966
P. abies	50–100	Nilsson and Hyppel, 1968
P. abies	55–100	Sokolov, 1958
P. abies	63–100	Hagner *et al.*, 1964
P. abies	80–100	Bonnemann, 1979
Picea sitchensis (Bong.) Carr.	5	Pawsey and Gladman, 1965
P. sitchensis	88	Shea, 1960
Picea glauca v. *albertiana* (Brown) Sarg.	76–97	Parker and Johnson, 1960
Abies concolor (Gord.) Hildebr.	24	Aho and Filip, 1982
Abies grandis (Dougl.) Lindl.	20–60	Maloy and Gross, 1963
A. concolor, *A. grandis*	17	Aho *et al.*, 1987
Abies lasiocarpa (Hook.) Nutt.	93–100	Parker and Johnson, 1960
A. lasiocarpa v. *arizonica* (Merr.) Lem	91–100	Hinds *et al.*, 1983
Larix kaempferi (Lambert) Carr.	4	Pawsey and Gladman, 1965
Pseudotsuga. menziesii (Mirb.) Franco	6	Childs and Wright, 1956
P. menziesii	21	Boyce, 1923
P. menziesii	13–42	Hunt and Krueger, 1962
P. menziesii	30	Thomas and Thomas, 1954
P. menziesii	57	Shea, 1961
Tsuga. heterophylla (Raf.) Sarg.	49	Rhoads and Wright, 1946
T. heterophylla	57	Englerth, 1942
T. heterophylla	61	Hunt and Krueger, 1962
T. heterophylla	63	Wright and Isaac, 1956
T. heterophylla	77	Wallis and Morrison, 1975
T. heterophylla	91–92	Shea, 1960, 1961
T. heterophylla	93	Englerth and Isaac, 1944
Acer rubrum L.	78	Pottle *et al.*, 1977
Acer saccharum Marsh.	100	Benzie *et al.*, 1963
Betula alleghaniensis Britt.	100	Benzie *et al.*, 1963
Eucalyptus spp.	66–100	White and Kile, 1993, 1994
Fagus sylvatica L.	64	Schumann and Dimitri, 1993
F. sylvatica	82	Schultz, 1973
Fraxinus excelsior L.	100	Schultz, 1973; Vasiliauskas and Stenlid, 1998b
Quercus alba L.	100	Shigo, 1972
Quercus robur L.	100	Schultz, 1973; Vasiliauskas 1998c
Q. rubra L.	100	Shigo, 1972
Quercus spp. (North American)	21	Roth and Hepting, 1943

10–50 per cent (Pechmann and Aufsess, 1971; Pechmann *et al*., 1973; Haas, 1975). In some forest areas, wound decay fungi were present in 41 per cent (Sima, 1982) or even as much as 79 per cent (Hagner *et al*., 1964) of the remaining trees.

Extent of decay in wounded stems

The infection by fungi of wounds on trees may result in serious wood degradation. Following wound infection, the decay in many tree species usually invades the central portion of the stem and a typical heartrot is formed that expands well above and below the wounds (Pawsey and Gladman, 1965; Shigo, 1966; El Atta and Hayes, 1987). Swedish studies have shown that, even when roots of spruce are damaged, the resulting decay may enter the stem and affect 1–4 m of its length (Hagner *et al*., 1964; Nilsson and Hyppel, 1968). Stem injury on white fir usually results in length reduction of 1.5–2 m of its commercially valuable timber (Aho and Simonski, 1975).

The extent of wound decay in tree stems is highly variable and is summarized for various tree species in Table 3. Both conifers and hardwoods seem to be susceptible to wound decay fungi, which usually spread several metres within the trunk. However, when compared with other tree species, beech and oak seem to exhibit more pronounced resistance to wound-invading microorganisms (Diehl and Seidenschnur, 1990; Vasiliauskas, 1998c). Apart from tree species, length of wound decay may depend on a number of other factors, such as wound age and size, and tree diameter. For Norway spruce it has been reported that wound decay proceeds faster from big wounds on larger stems, and that its length increases over time (Vasiliauskas, 1998a, and references therein). For example, a Swedish study showed that the extension of decay from 10-year-old injuries was in most cases 2–3 m, whereas from 33-year-old injuries it was over 5 m (Nilsson and Hyppel, 1968). Rather similar results were obtained in Lithuania, where the average length of decay from 10-year-old wounds was 3 m, and in 25-year-old wounds it was 4 m (Vasiliauskas, 1993). In extreme cases, wound rot in Norway spruce may devalue >10 m of a trunk (Aufsess, 1978). Decay resulting from root collar injuries and wounds higher on the trunk within the same period of time is approximately equal in length (Steyrer, 1992; Vasiliauskas, 1993).

The proportion of wound decay volume in the stems of injured spruce may therefore reach 48 per cent in extreme cases, although on average it was much lower, at 12 per cent (Kallio and Tamminen, 1974). As a result, in each wounded trunk towards maturity, 16–50 per cent of first quality roundwood passes into fuelwood or low quality pulpwood (Fanta, 1958; Zaruba, 1963; Hagner *et al*., 1964; Kowalski and Skabara, 1966; Sima, 1982; Kato, 1984; Igolkina, 1990; Vasiliauskas, 1993).

Wound decay-causing fungi have been investigated in detail in conifer tree species. *Stereum sanguinolentum*, *Amylostereum areolatum* and *Amylostereum chailletii* are the most typical conifer wound decay fungi, both in Europe and in North America (Aufsess, 1980; Table 3). The biology of *S. sanguinolentum* was reviewed by Vasiliauskas (1998a), and that of *Amylostereum* spp. by Talbot (1977) and Thomsen (1996). *Amylostereum* species are symbiotic with siricid woodwasps, which in a number of cases were shown to introduce these fungi into the living stems of spruce with mechanical damage (Vasiliauskas *et al*., 1998).

Wound closure

When the bark is torn from living trees, as in logging wounds or in other types of mechanical injury, the vascular cambium cells are removed or destroyed, and callus starts to develop from around the living bark at the margin of the wound, growing towards the centre of the wound (Neely, 1979). Wound closure on trees consists principally of post-injury radial growth rings that are deposited each year on the wound surface; thus it occurs during the growing season and the wound closure rate is determined by the annual increment of radial growth at the wound site (Neely, 1970, 1979). The occurrence of trees with closed wounds in forest stands is not uncommon (Bazzigher, 1973; Vasiliauskas, 1994, 1998c; Vasiliauskas and Stenlid, 1998b). For example, among spruce with bark-stripping damage, the proportion of trees with closed injuries may be as high as 80–94 per cent (Staines and Welch, 1984).

Table 3: Extent of discoloration and/or decay in stems of forest trees following wound infections

Tree species	Tree age (years)	Stem d.b.h. (cm)	Period since injury (years)	Affected stem length (m)	Main fungi, causing deterioration	Source
Picea abies	–*	over 8	2	0.5	*Stereum sanguinolentum* (Alb. & Schw.:Fr.) Fr.	Solheim and Selås, 1986
P. abies	25	14	2.5	0.2–2.4	*S. sanguinolentum, Amylostereum areolatum* (Fr.) Boid.	Koch and Thongjiem, 1989
P. abies	40–60	–	3	2.0–2.5	*S. sanguinolentum, A. areolatum*	Aufsess, 1978
P. abies	24	10	5	2.0–3.3	*S. sanguinolentum*	Risley and Silverborg, 1958
P. abies	30	–	5–6	1.0–1.8	*S. sanguinolentum*	Pawsey and Stankovicova 1974
P. abies	31–54	–	4–8	1.4–1.5	*S. sanguinolentum*	El Atta and Hayes, 1987
P. abies	50	–	4–14	1.3–3.8	*S. sanguinolentum*	Sokolov, 1958
P. abies	50	10–20	7	1–4	*S. sanguinolentum*	Vasiliauskas and Stenlid, 1998c
P. abies	50–60	8–27	7–25	1–8	*S. sanguinolentum, Sistotrema brinkmannii* (Bres.) J.Erikss	Vasiliauskas, 1998d
P. abies	40–60	–	14–40	1.5–5.0	*S. sanguinolentum*	Schedrova, 1959
P. abies	60–120	18–24	10–15	3.0–3.5	*S. sanguinolentum*	Ekbom, 1928
P. abies	70	–	12	1–6	*S. sanguinolentum*	Hakkila and Laiho, 1967
P. abies	90–100	10–40	–	4	*S. sanguinolentum*	Kallio and Tamminen, 1974
P. abies	50–60	7–28	7–24	1–4.5	*Amylostereum chailletii* (Fr.) Boid., *A. areolatum*	Vasiliauskas, 1999
P. abies	60–120	–	10–80	2–15	*S. sanguinolentum, A. areolatum*	Pechmann and Aufsess, 1971
P. abies	30–120	8–42	2–25	1.3–4.5	*S. sanguinolentum, Postia stiptica* (Pers.:Fr.) Jül.	Vasiliauskas, 1989, 1993
P. abies	60–100	–	10	2–3	*S. sanguinolentum, P. stiptica*	Cerny, 1989
P. abies	38–100	18–42	10–33	2.5	*S. sanguinolentum, Heterobasidion annosum* (Fr.) Bref.	Nilsson and Hyppel, 1968
P. abies	110	–	12	0.7	–	Kärkkäinen, 1971
P. abies	85	–	4–5	2.6	*S. sanguinolentum, A. areolatum, P. stiptica*	Kovbasa, 1996
P. abies	–	12–52	–	2.4–7.2	–	Gorshin, 1935
P. abies	–	15–55	–	2.2–8.3	–	Vakin, 1927
Abies grandis	15–90	–	–	2.2	*Echinodontium tinctorium* Ell. & Ev.	Maloy and Gross, 1963
A. grandis, A. concolor	43–115	9–20	0–108	0–8.6	*E. tinctorium, H. annosum*	Aho *et al.*, 1987
Abies lasiocarpa	130	30–40	15–31	5.1–9.4†	*A. chailletii, S. sanguinolentum*	Parker and Johnson, 1960
Abies lasiocarpa	57–156	13–45	11–17	0.4–4.2†	*A. chailletii, S. sanguinolentum*	Hinds *et al.*, 1983
Abies nordmanniana Spach	200–400	–	100	8	*Schizophyllum commune* Fr.	Shtraukh-Valeva, 1954
Picea glauca	110–170	30–40	15–31	5.8–6.6†	*S. sanguinolentum, Coniophora puteana* (Schum:Fr) Karst	Parker and Johnson, 1960

Continued

Table 3: *Continued*

Tree species	Tree age (years)	Stem d.b.h. (cm)	Period since injury (years)	Affected stem length (m)	Main fungi, causing deterioration	Source
Pseudotsuga menziesii	45–57	23–41	3–9	0.3–1.2†	*H. annosum*	Hunt and Krueger, 1962
P. menziesii	114	–	10	1.4†	*Fomitopsis pinicola* (Fr.) Karst.	Shea, 1961
Tsuga heterophylla	45	–	5–25	1–12†	*H. annosum, S. sanguinolentum, A. chailletii*	Wallis and Morrison, 1975
T. heterophylla	50	–	10	6†	*S. sanguinolentum*	Shea, 1961
T. heterophylla	61	27	3–5	3.4†	*H. annosum*	Hunt and Krueger, 1962
T. heterophylla	–	60	12	0.8	*H. annosum, F. pinicola*	Englerth and Isaac, 1944
Acer rubrum	–	15–25	2	0.2	–	Leben, 1985
A. rubrum	–	15–25	3	0.9	*Graphium* sp., *Phialophora* sp.	Houston, 1971
Betula alleghaniensis	–	15–25	3	2.4	*Graphium* sp., *Phialophora* sp.	Houston, 1971
Betula pendula	30–40	13–25	1	1.5–2.0	–	Dujesiefken *et al.*, 1991
Eucalyptus spp.	23–75	–	5–23	2–6	–	White and Kile, 1994
Fagus sylvatica	80–135	30–70	9–25	3–10	*Fomes fomentarius* Fr., *Ganoderma applanatum* (Pers) Pat	Vanik, 1979
F. sylvatica	34	4–13	1–18	0–0.8	–	Volkert *et al.*, 1953
F. sylvatica	30–40	13–25	1	0.1	–	Dujesiefken *et al.*, 1991
F. sylvatica	100–170	25–45	2	1–4	–	Dujesiefken and Liese, 1990
Fraxinus excelsior	50	20	5–18	8–9	*Phaeoacremonium* sp., *Libertella* spp.	Vasiliauskas and Stenlid 1998b
F. excelsior	30–40	13–25	1	0.5–1.5	–	Dujesiefken *et al.*, 1991
Liriodendron tulipifera L.	30–60	8–35	2	1	*Ceratocystis* sp., *Phialophora* sp.	Shortle and Cowling, 1978
Liquidambar styraciflua L.	30–60	8–35	2	0.5	*Ceratocystis* sp., *Fusarium* sp.	Shortle and Cowling, 1978
Populus tremuloides Mich.	–	14–29	3	0.5–1.9	*Peniophora polygonia* Fr., *Bjerkandera adusta* (Fr.) Karst.	Laflamme, 1979
Quercus robur	33	15	15	1.3	*C. puteana*, *Stereum hirsutum* (Willd.:Fr.) S.F.Gray	Vasiliauskas, 1998c
Q. robur	30–40	13–25	1	0.2–1.3	–	Dujesiefken et al., 1991

*Not reported.
†Percentage of tree volume lost by decay (%).

A significant relationship exists between the initial wound surface area and incidence of complete occlusion. In Sitka spruce plantations, all stem wounds with an initial size <60 cm^2 were fully closed over a 15-year period, but none of >180 cm^2 initial size closed in the same time period (Welch *et al.*, 1997).

Wound closure on forest trees may be a very important factor, restricting the colonization of wound-invading fungi. In beech, for example, complete closure without infection was noted in all wounds initially <5 cm wide, in 70 per cent of wounds 5–8 cm wide and in 50 per cent of wounds >8 cm wide (Hosius, 1967). Moreover, in some tree species, such as spruce (Schedrova, 1959; Löffler, 1975; Vasiliauskas, 1994) and oaks (Toole, 1967; Vasiliauskas, 1998c), wound closure not only prevents further infections, but is able to stop subsequent fungal development in already infected wounds. In contrast, in wounded stems of ash wound, occlusion had no noticeable effect on development of stain and decay (Vasiliauskas and Stenlid, 1998b).

Rate of wound closure is positively correlated with radial growth of the tree in Norway spruce (Schedrova, 1959; Beitzen-Heineke and Dimitri, 1981; Vasiliauskas, 1994), ash and oak (Neely, 1970, 1979; Vasiliauskas and Stenlid, 1998b; Vasiliauskas, 1998c). This indicates that tree vigour is of great importance in wound closure. Table 4 summarizes wound closure rates in different tree species. It is obvious that Norway spruce is slow to close wounds. Larger and older wounds on Norway and Sitka spruce close more slowly (Staines and Welch, 1984; Vasiliauskas 1994; Welch *et al.*, 1997). Despite the cessation of fungal development in damaged stems, wound closure in spruce stands can therefore influence fungal colonization in small injuries only and is of little practical importance in preventing decay development from 5–10 cm broad scars. In an early Czech report it was stated that it generally takes 20–30 years for complete closure of 5–10 cm broad wounds on Norway spruce (Kessl *et al.*, 1957). This time corresponds well with the wound closure rates that are presented in Table 4. It is therefore very common that, following wounding, xylem on living Norway spruce remains exposed for many years.

Loss in wood value at the final harvest

Since logging injury usually occurs on the lower part of a trunk, wound decay in a tree affects the most valuable timber (Wallis and Morrison, 1975). The value of injured and decayed spruce trunks was reported to be 30 per cent lower when compared with sound trunks of identical size (Hasek, 1965; Hakkila and Laiho, 1967). Depending on the frequency and severity of damage in stands of spruce, financial revenues at final harvesting may decrease by 7–20 per cent because of wound decay (Fanta, 1958; Hilscher, 1964; Steyrer, 1992). For example, in spruce stands where up to 80 per cent of stems had stem wounds, saw-log yield at the final harvest decreased by 20 per cent (Guy, 1983). In a

Table 4: Wound closure rates of forest trees

Tree species	Wound closure rates (cm year^{-1})	Closure period of 10 cm broad wound (years)	Source
Picea abies	0.2–0.4	25–50	Bonnemann 1979; Vadla 1989; Vasiliauskas 1994
Acer saccharrum	2.0	5	Skilling, 1958
Eucalyptus spp.	1.3–1.5	7–8	White and Kile, 1993, 1994
Fagus sylvatica	0.6–1.0	10–15	Volkert *et al.*, 1953
Fraxinus americana L.	1.2	8	Neely, 1970
Fraxinus excelsior	1.3	7–8	Vasiliauskas and Stenlid, 1998b
Quercus palustris Muench	1.7	6	Neely, 1970
Quercus robur	1.0	10	Vasiliauskas, 1998c
Quercus spp.	0.5–0.7	14–20	Roth and Hepting, 1943
Ulmus americana L.	1.4	7	Skilling, 1958

118-year-old spruce stand where 51 per cent of standing trees had been damaged by selective logging 17 years previously, wound decay devalued the total timber harvest by 16 per cent (Fanta, 1958). In an 85-year-old stand of spruce where 6 per cent of trees had 5-year-old logging injuries, saw-log yield was found to decrease by 11 m^3 ha^{-1} (Kovbasa, 1996).

In North America, an annual loss to decay of 0.75 per cent of the gross volume was recorded in western hemlock trees injured during logging (Wallis and Morrison, 1975). In mature hemlock with 5–30-year-old logging wounds, 41 per cent of the gross increment of the infected trees since logging was lost to decay (Wright *et al*., 1947). Another study showed that in hemlock stands 0.7 m^3 ha^{-1} was lost each year due to decay entering thinning wounds, which averaged 5.5 per cent of the net periodic annual increment, whereas in stands of Douglas fir annual loss comprised only 0.1–0.2 m^3 ha^{-1}, or 0.1–2.7 per cent of the annual increment of a stand (Hunt and Krueger, 1962). In maple and birch stands, value loss from skidding wounds was also reported to be low (Ohman, 1970).

During recent decades in central Europe, spruce stands free of damage have been rare (Schimitschek, 1975; Cervinkova, 1980; Steyrer, 1992). The forest survey in Austria in 1961–70 revealed a loss of 30 million m^3 of wood following logging injury (Schimitschek, 1975). The actual losses might be higher, since spruces in most cases are wounded at the age of 30–50 years, and therefore another 30–50 years may pass until final harvesting (Vasiliauskas, 1993). Consequently, wound decay is currently regarded as a threat to sustainable timber yields and one of the main reasons for financial losses in forest management (Steyrer, 1992). Financial losses have been reported to be very significant. For example, in the spruce stands of Lower Saxony the annual loss due to wound decay following logging damage was 1 million DM (Kato, 1969). Annual losses caused by wound decay in spruce stands damaged by logging in Baden-Württtemberg were reported to amount to 25 million DM (Dietz, 1981). The economic losses caused in Sweden by stem and root damage during harvesting were considered to vary from 200 to 430 SEK ha^{-1}, depending on the harvesting technique used (Dehlen, 1977).

For conifers in North America, models for assigning decay volumes to wounds of known age and size have been published by Wright and Isaac (1956), Aho and Simonski (1975) and Wallis and Morrison (1975). In Lithuania, an attempt has been made by Vasiliauskas and Juška (1999) to model standing volume loss due to wound decay in stands of spruce (*Picea abies*), ash (*Fraxinus excelsior*) and oak (*Quercus robur*). Such models, presented in Figures 1–3, are based on empirical data accumulated in a number of separate studies (Vasiliauskas, 1993, 1994, 1998c, 1998d, 1999; Vasiliauskas and Stenlid, 1998b, 1998c). It has been estimated that the percentage of standing volume affected by decay is lower in older stands,

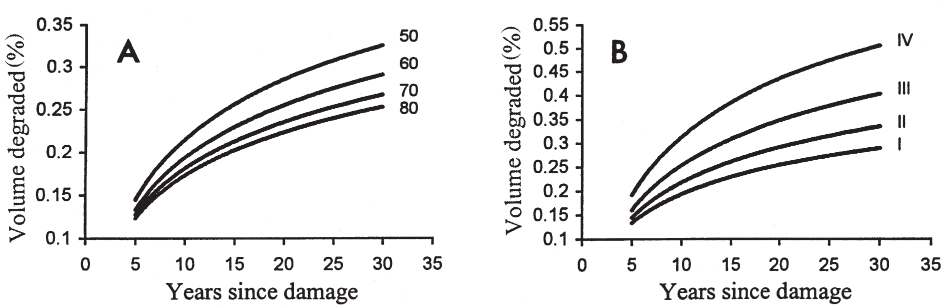

Figure 1. Percentage of stand volume degraded by wound decay in spruce stands of normal density (coverage 1.0), containing 1 per cent of wounded stems: (**A**) in stands of first quality class (bonität I), depending on age of damage and stand age (50, 60, 70 and 80 years); (**B**) in 60-year-old stands, depending on age of damage and stand quality class (bonitäts I, II, III and IV) (from Vasiliauskas and Juška, 1999).

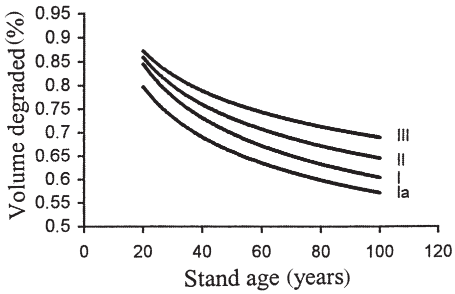

Figure 2. Percentage of stand volume degraded by wound decay in ash stands of normal density (coverage 1.0), containing 1 per cent of wounded stems, depending on stand age and stand quality class (bonitäts Ia, I, II and III) (from Vasiliauskas and Juška, 1999).

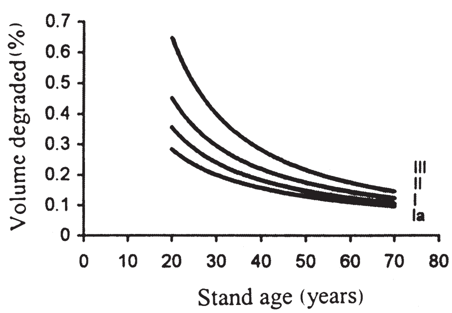

Figure 3. Percentage of stand volume degraded by wound decay in oak stands of normal density (coverage 1.0), containing 1 per cent of wounded stems, depending on stand age and stand quality class (bonitäts Ia, I, II and III) (from Vasiliauskas and Juška, 1999).

and in stands of higher quality class (bonität); in cases where 100 per cent of trees possess wounds, 15–40 per cent of the standing volume would be degraded in stands of spruce, 60–90 per cent in stands of ash and 10–70 per cent in stands of oak (Figures 1–3). The data for spruce agree with other related studies (Baader, 1956; Kessl *et al.*, 1957; Szczerbinski, 1959; Hilscher, 1964; Zaruba and Snajdr, 1966; Kowalski and Skabara, 1966; Kato, 1969, 1984; Speidel, 1980; Steyrer, 1992). Financial losses are expected to be more significant in older stands of higher quality classes; where 100 per cent of trees are damaged in an 80-year-old, normally stocked (coverage 1.0) stand of the highest quality class, financial losses would approximate 2000–2500 US$ ha^{-1} in stands of spruce and oak, and 5000 US$ ha^{-1} in stands of ash (Vasiliauskas and Juška, 1999).

Control of wounding and decay

Damage to standing trees during forest operations is caused exclusively by human activities. Wound decay that develops in forest stands from logging wounds could therefore be controlled simply by minimizing the damage to stems and roots. This aim can be achieved by proper planning of the forest operations, training of the workers and adequate supervision (Hasek, 1965; Yde-Andersen, 1976; Dimitri, 1983; Kallio, 1984). Cases were reported when residual stand damage was mostly influenced by the care taken in harvest planning and the experience of the equipment operators (Cline *et al.*, 1991). Many studies have been conducted in conifer stands to check how different harvesting methods influence the extent of damage to the residual growing stock (Fanta, 1959; Kärkkäinen, 1969, 1970, 1973; Abetz, 1972; Horndasch, 1975; Soukup and Temmlova, 1977; Dietz, 1981; Jäger, 1981; Rieger and Pfeil, 1981; Siren, 1981, 1982; Bredberg and Wästerlund, 1983; Kallio, 1984; Athanassiadis, 1997). As a result, a number of silvicultural and operational options have been suggested to minimize injury to the remaining trees during forestry operations, and these have been reviewed by Dimitri (1983).

In spite of preventive measures, logging damage cannot be completely avoided in practice. Therefore, to minimize wounding in spruce stands, breeding of trees with a thick bark has been considered (Rohmeder, 1971). In order to control wound infection by decay fungi, a number of wound dressings have been tested to prevent wound decay in forest stands. Pioneering tests of several wound dressings have been carried out in Germany and the Czech Republic, and some of the substances were able to restrict the spread of decay in spruce (Rohmeder, 1939, 1953; Fanta, 1961). Starting in the 1970s, extensive studies on chemical wound decay control in spruce took place in Germany (Dimitri and Schumann, 1975; Schönhar, 1979; Ueckermann *et al.*, 1979; Bonnemann, 1980; Beitzen-Heineke and Dimitri, 1981; Dietz, 1981; Olberg-Kallfass and Schönhar, 1982; Dimitri, 1984; Lam *et al*., 1984; Schumann, 1985). The results show that for successful protection against fungi, wound dressings must have the following main properties: (1) high viscosity, ensuring mechanical coverage; (2) long-term elasticity, thus preventing peel-off or cracking following tree growth; (3) resistance to climatic factors; (4) ease of application and good adhesion to the moist wood; (5) however, their fungitoxicity is of little importance (Bonnemann, 1980). Out of many tested substances four were found to be highly efficient in preventing wound infection in Norway spruce and are permitted for use in practical forestry (Dimitri, 1984). The cost of the treatment was 2.0–2.4 DM per wound (Lam *et al*., 1984), which was only a fraction (10–20 per cent) of the losses which would have occurred if wounds could not be treated (Dimitri, 1984). In particular, wounds on trees in valuable final-crop spruce stands should be protected, since in this case average total costs amount to only 4–13 per cent of the losses expected without treatment (Beitzen-Heineke and Dimitri, 1981). Wound dressings must be applied as soon as possible after the injury has been inflicted, i.e. immediately after the thinnings or other operations in a stand are completed (Bonnemann, 1980; Beitzen-Heineke and Dimitri, 1981; Olberg-Kallfass and Schönhar, 1982).

The deuteromycete *Epicoccum purpurascens* Ehrenb. ex Schlecht. has recently been tested as a potential biological control agent against wound pathogens on stems of spruce, and has had a significant influence on the composition of the mycoflora of the wounds, analysed 8 months after application (Zimmermann *et al*., 1995).

However, there is really no convincing evidence that these wound dressings work in preventing decay in the long run. Therefore it is more appropriate to encourage the forest workers to adopt methods which avoid damage to retained trees during forestry operations.

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