

Tree Mortality after Prescribed Burning in an Old-Growth Scots Pine Forest in Northern Sweden

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Tree mortality and input of dead trees were studied after a prescribed burning in a forest reserve in northern Sweden. The stand was a multi-layered old-growth forest. The overstorey was dominated by Scots pine (*Pinus sylvestris* L.) and the understorey consisted of mixed Scots pine and Norway spruce (*Picea abies* L. Karst.). Ground vegetation was dominated by ericaceous dwarf-shrubs and feathermosses. The stand has been affected by six forest fires during the last 500 years. The prescribed burning was a low intensity surface fire that scorched almost 90 % of the ground. Tree mortality for smaller pines and spruces (DBH < 10 cm) was over 80 % in the burned parts of the reserve. For larger pines, 10–50 cm DBH, mortality showed a decreasing trend with increasing diameter, from 14 % in class 10–20 cm DBH to 1.4 % in class 40–50 cm DBH. However, pines with DBH ≥ 50 cm had a significantly higher mortality, 20 %, since a high proportion of them had open fire scars containing cavities, caused by fungi and insects, which enabled the fire to burn inside the trunks and hollow them out. The fire-induced mortality resulted in a 21 m³ ha⁻¹ input of dead trees, of which 12 m³ ha⁻¹ consisted of trees with DBH ≥ 30 cm. An increased mortality among larger trees after low-intensity fires has not previously been described in Fennoscandian boreal forests, probably owing to a lack of recent fires in old-growth stands. However, since large pines with open fire scars were once a common feature in the natural boreal forest, we suggest that this type of tree mortality should be mimicked in forestry practices aiming to maintain and restore natural forest biodiversity.

Keywords coarse woody debris, dead trees, forest fire, forest management, nature conservation, tree mortality

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1 Introduction

The Fennoscandian boreal forest used to be affected by recurrent fires started by lightning or human activity; sometimes accidental, but often deliberate, to improve pasture or for slash-and-burn cultivation (Pettersson 1941, Arnborg 1949, Viro 1969, Granström 1993, 1995, Andrén 1996, Parviainen 1996). Historically, the average fire interval has varied substantially depending on a number of factors, including climate, altitude, site type, human impact, and landscape structure (Kohh 1975, Zackrisson 1977, Linder et al. 1997, Niklasson and Granström in press). However, during the mid- to late-1800s, wildfires ceased almost totally in the Swedish boreal forest, because of an increasing awareness of the vast timber value of the forests and measures taken to control fire (Kohh 1975, Zackrisson 1977).

During the last decade, the ecological importance of forest fires in the boreal forest has received increased scientific attention (Schimmel and Granström 1996, Zackrisson et al. 1996, Wardle et al. 1997). At the same time, consideration of environmental issues, including maintenance and restoration of biodiversity, has been an urgent matter in forestry. As a result of this development, several burnings for conservation purposes have been carried out by forest companies and nature conservation authorities in Scandinavia (Tanninen et al. 1994).

The majority of forest-living species that are registered on the Swedish red data lists depend on dead trees (Berg et al. 1994). Furthermore, some of these species are believed to be totally confined to fire-killed trees (Ehnström et al. 1993). To maintain vital populations of these species, and to imitate the disturbance pattern of natural forests, several silvicultural models including the use of prescribed burning, or fire mimicking practices, have been introduced (Angelstam and Pettersson 1997, Fries et al. 1997). However, the scientific bases of such models are limited. Hitherto, most burnings for conservation purposes in Scandinavia have been carried out in managed stands, i.e. stands with little or no similarity to the natural forest. Consequently, the ecological effects of fires in such stands (e.g. Kolström and Kellomäki 1993, Ehnström et al. 1995, Wikars 1995) may differ substantially from

those of fires in natural forests. Therefore, there is a considerable need of knowledge about the effects of fires on stand dynamics in natural forests. Such knowledge is crucial for forest managers developing silvicultural guidelines designed to promote stand dynamics resembling those of natural forests.

The aim of this study was to obtain data on fire-induced tree mortality, input of dead trees and changes in stand structure after a prescribed burning in an old-growth forest, i.e. a forest containing a multi-storied tree layer, a large number of large diameter trees, standing dead trees (snags), dead windthrown trees (downed logs), and old trees of low vitality (cf. Peterken 1996).

2 Material and Methods

2.1 Study Area

The forest reserve “Kåtaberget” is situated in the county of Västerbotten, northern Sweden (Fig. 1) within the middle boreal forest zone (Ahti et al. 1968). The reserve covers 10 hectares and is situated on a south-facing slope (277–315 m.a.s.l.). Eighty six percent of the ground area is dry to mesic, while the rest is moist to wet. On the dry-mesic sites the soil is an iron podzol with a sandy loam texture.

The historical human impact on the reserve has been insignificant, which has permitted old-growth structures such as a large number of old trees, snags and downed logs to develop. In 1995, the owner performed a prescribed burning in the reserve; the first prescribed burning of a true old-growth forest in Sweden.

Before the prescribed burning, the forest was characterised by a multi-layered tree canopy dominated by old, large-diameter Scots pines (*Pinus sylvestris* L.) with a dense understorey of pine and Norway spruce (*Picea abies* L. Karst.) (Fig. 5). A few silver birches (*Betula pendula* Roth), hairy birches (*B. pubescens* Ehrh.) and grey alders (*Alnus incana* L.) were also present, as well as a few scattered goat willows (*Salix caprea* L.).

The fire history of the reserve was established through dendrochronological analyses of 17 wood samples from old pines, snags and charred stumps

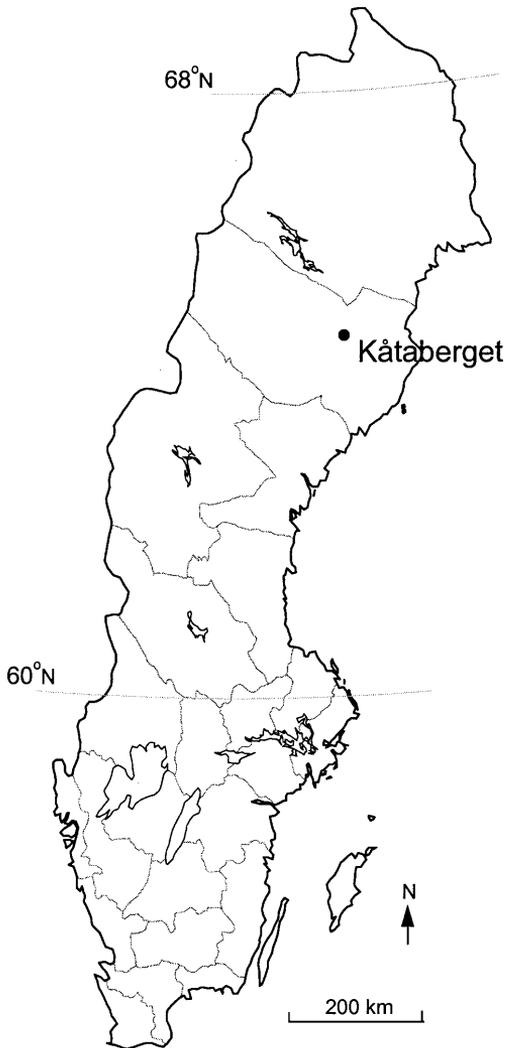


Fig. 1. The location of the study site (64°50'N, 18°49'E).

containing fire-scars. Fire years were dated by the cross-dating technique described in Stokes and Smiley (1968) and Niklasson et al. (1994). The last fire was dated to 1853, and six more fires were dated back to the 1300s (Fig. 2). The mean fire interval before the last fire (1853) was 80 years.

The stand structure was strongly influenced by previous forest fires. For instance, pines created a multi-aged stand of several cohorts, typical of fire-regenerated stands (Zackrisson 1980, Jonsson 1997, Linder et al. 1997, Niklasson et al. unpublished) and on dry-mesic ground there were no older spruces present, indicating that no spruces survived the last fire in 1853. Furthermore, a large proportion (55 %) of the living pines with DBH ≥ 30 cm had visible fire scars from previous fires.

According to the sample plot survey (see 2.3 Field Measurements), the standing volume of living trees was ca. 270 m³ ha⁻¹; 96 % pine, 2 % spruce and 2 % deciduous, by volume, before the fire. The total stem number was ca. 2400 trees ha⁻¹ (56 % pines, 38 % spruces and 5 % deciduous trees). Eighty-three percent of the trees were < 10 cm in DBH (diameter at breastheight, i.e. 1.3 m above ground) while ca. 180 stems ha⁻¹ (7 %) were ≥ 30 cm in DBH. Coarse woody debris (DBH ≥ 10 cm) amounted to 24 m³ ha⁻¹, comprised almost exclusively of snags (36 ha⁻¹) and downed logs (17 ha⁻¹) of pine.

The field layer was dominated by dwarf shrubs such as *Vaccinium vitis-idaea* (L.) and *Vaccinium myrtillus* (L.). In drier spots, *Empetrum hermaphroditum* (Hagerup) was the most common species. Herbs and grasses were sparse. The bottom layer in mesic sites was dominated by the pleurocarpous mosses *Pleurozium schreberi*

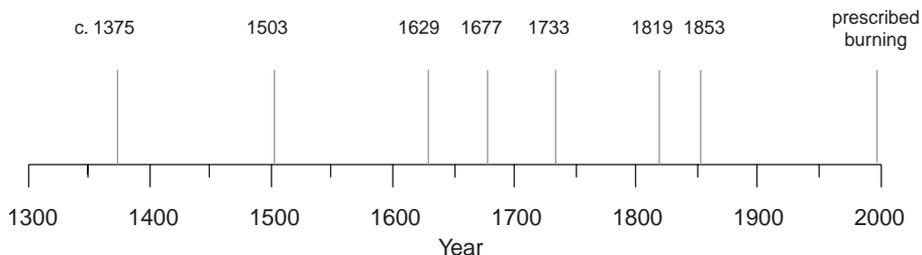


Fig. 2. Dated fire years in Kåtaberget forest reserve.

(Brid.) Mitt. and *Hylocomium splendens*. (Hedw.) B.S.G., and in moister spots *Ptilium crista-castrensis* (Hedw.) De Not. appeared as well. On drier ground, lichens of the genus *Cladina* sp. were present. These species normally dry out within a week after rain, and then quite readily spread fire (Schimmel and Granström 1997).

2.2 The Prescribed Burning

The reserve was strip-burned on the 27th of June 1995. First, the southern part of the reserve, adjoining a lake, was burned. Then fire was successively ignited along lines ca. 20 m further north, crossing the reserve from west to east, allowing the firefront to run freely with the wind southwards to the formerly burned area. The burning started at 11 a.m. and was finished by 6 p.m. the same day. The fire was easy to control due to a low spread rate and extensive protective measures involving ditches and watered borders.

The fire was of low intensity, the fire front intensity (cf. Byram 1959) was lower than 700 kW m^{-1} . The average fire spread was about 2 m min^{-1} and the flames rarely reached above 1 m (J. Schimmel, unpublished). In some sections, the fire was allowed to spread freely with the wind for ca. 50 m, but even in these sections the rate of fire spread was only occasionally greater than 2 m min^{-1} , and the fire intensity was still low (J. Schimmel, unpublished). Wind speed in the stand was then around 2 m s^{-1} . However, the most important factor restricting fire intensity was the quite high moisture content in the finer fuel fractions on the ground (ca. 20 % moisture was found in the upper parts of the moss layer, [J. Schimmel, unpublished]).

2.3 Field Measurements

In October 1995, scorched ground, stand structure and post fire mortality were estimated. The extent of scorched ground and the distribution of forest vegetation types were evaluated in a strip survey. Eight 0.5 m wide parallel transects were laid out in N–S direction, at intervals of 20 m with a randomly-located starting point, where the lengths of scorched and unscorched ground

was measured in metres. Forest vegetation type was determined according to the classification by Hägglund and Lundmark (1977). The total strip length was 3500 m.

Data on stand structure and tree mortality in the burned parts of the forest were collected from 31 square plots, each 0.04 ha in size ($20 \text{ m} \times 20 \text{ m}$). They were laid out in a systematic $70 \text{ m} \times 50 \text{ m}$ grid, placed in N–S direction. The starting point was located randomly. Tree status, i.e. living, standing dead (snag), or lying dead (downed log), was determined for all tree specimens, in each plot, and the DBH was recorded for all standing trees at a height of 1.3 m and for all downed logs. For all dead trees, judgement was passed on whether or not death was caused by the prescribed burning. Trees with only red or brown needles left, trees that were defoliated after the fire (easily detectable by the presence of large amounts of dead needles on the scorched ground), and burned-out, broken trees were classified as killed by the fire. Standing trees that were severely damaged by the fire, but still had some green foliage were recorded as living. The abundance of fire scars in living trees from previous fires was also recorded. Finally, we recorded the tree height of all living trees on six of the plots (height sample trees) for the standing volume calculations.

2.4 Calculations

Stem volumes were calculated for every tree, snag and log as total stem volume, including bark over stump height, using secondary volume functions. These functions were calculated in two steps. Firstly, stem volumes for the height-sample trees ($n = 174$) were calculated, using volume functions presented by Andersson (1954) for trees with $\text{DBH} < 5 \text{ cm}$, and by Brandel (1990), for trees with $\text{DBH} \geq 5 \text{ cm}$. Secondly, the calculated volumes were used to compute secondary volume functions for pine and spruce with diameter as an independent variable. A non-linear regression model was used, where $\text{vol} = a \times d^b$, where $\text{vol} = \text{stem volume in m}^3$, $d = \text{DBH in cm}$ and a and b are constants. The regressions were calculated using the Simplex minimisation method (SYSTAT 1992).

The secondary functions used in this study were:

$$\text{vol}_{\text{pine}} = 2.8036 \times 10^{-4} \times d^{2.273}$$

corrected $r^2 = 0.98$

$$\text{vol}_{\text{spruce}} = 6.0157 \times 10^{-5} \times d^{2.801}$$

corrected $r^2 = 0.99$

From the diameter data of living trees, trees killed by the fire and old dead trees, it was possible to reconstruct the stand structure before the fire.

To examine if the differences in mortality of different size-classes were statistically significant we made an logistic regression (SPSS 1993), in which the different size-classes were tested against one another. This method was used since data were bernoulli-distributed.

3 Results

For trees with DBH < 10 cm, mortality was very high among both pines and spruces (90 % and 81 %, respectively). For larger trees, mortality showed a decreasing trend with increasing diameter up to DBH-class 40–50 cm, in which trees

had a mortality of 1.5 % (Fig. 3). However, pines with DBH ≥ 50 cm had a mortality of 20 % (Fig. 3), which did not follow the general trend of decreasing mortality. The mortality in this size class was significantly higher than in diameter classes DBH 30–40 cm and DBH 40–50 cm ($B = 1.7088$, S.E. = 0.4398, $p = 0.0001$, and $B = 2.6365$, S.E. = 0.8763, $p = 0.0026$, respectively). In total, the number of living trees was reduced by the fire from ca. 2400 ha^{-1} to 670 ha^{-1} .

The size-related mortality trend was obvious among the smallest trees, since mortality dropped from almost 100 % for trees with DBH 0–2 cm, to ca. 20 % for trees with DBH 10–12 cm (Fig. 4). Mortality among the deciduous trees showed a similar pattern to spruce, but because of the small numbers of such trees we have omitted data showing this from the presentation. The fire eliminated most of the undergrowth in the smaller size-classes and changed the diameter distribution considerably in the reserve (Fig. 5). The prescribed burning affected almost the entire reserve. In total, 88 % of the ground was scorched, including 94 % of the dry-mesic ground, but only 44 % of the moist-wet ground.

As a result of the fire, there was a substantial input of dead trees. In total, 21 $\text{m}^3 \text{ha}^{-1}$ of the stand volume was converted from living to dead

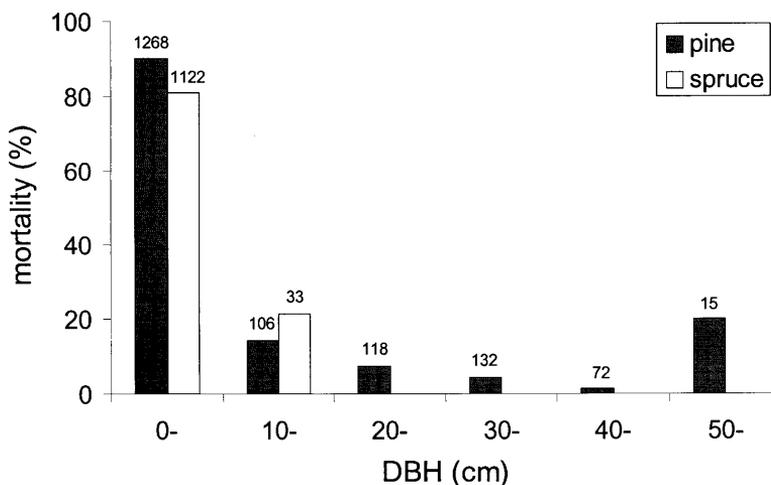


Fig. 3. Tree mortality caused by the prescribed burning. There were no spruces larger than DBH = 20 cm. The total number of trees recorded in each size-class is shown above the staple bars.

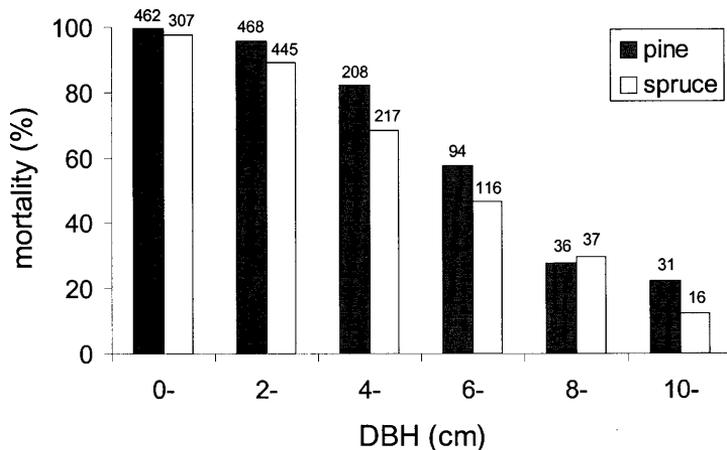


Fig. 4. Mortality of small diameter trees (DBH < 12 cm). The total number of trees recorded in each size-class is shown above the staple bars.

Table 1. Input of dead trees due to the prescribed burning.

DBH (cm)	Input of dead trees ($\text{m}^3 \text{ha}^{-1}$)	
	Pine	Spruce
0–	3.0	1.4
10–	1.3	0.4
20–	3.0	-
30–	3.8	-
40–	1.0	-
50–	7.2	-
Total	19.4	1.8

material, and more than one third, $7.2 \text{ m}^3 \text{ha}^{-1}$, originated from pines with $\text{DBH} \geq 50 \text{ cm}$ (Table 1). As a result of this input, the volume of dead trees with $\text{DBH} \geq 10 \text{ cm}$ increased by ca. 60 % in the reserve.

4 Discussion

The high mortality recorded among small diameter trees in Kåtaberget is in accordance with previous studies which include reports of size-dependent mortality trends, i.e. mortality decreases

with increasing DBH or height (McCarthy and Sims 1935, Hare 1965, Sepponen 1989, Kalabodikis and Wakimoto 1992, Kolström and Kellomäki 1993). This phenomenon is usually explained by the thinner bark and lower foliage position of smaller trees. The amplitude of such trends is variable and depends on a number of factors, including tree species and fire intensity (Hare 1965). The strong trend from high to low mortality in the 0–12 cm DBH interval (Fig. 4) found in this study supports the recorded intensity data (Schimmel, unpublished).

The prescribed burning also resulted in a high mortality for pines with $\text{DBH} \geq 50 \text{ cm}$ (Fig. 3), which was a rather surprising phenomenon, not previously described. The increased death rate of these pines was exclusively caused by the burning out of trees with open fire scars, which had cavities caused by fungi (*Phellinus pini* (Fr.) Ames) or carpenter ants (*Camponotus* sp.). Exposed dry wood in fire scars often burns for a short while when the fire front passes, but if the wood contains cavities the fire may persist for several hours after the fire front has passed. The fire may then burn into the heartwood, hollow the trunks, and eventually cause their downfall (Fig. 6). Most of the burned-out trees in Kåtaberget fell to the ground within a couple of days after the fire, but occasional fellings of less severely damaged trees during strong winds occurred several months later (personal observation).

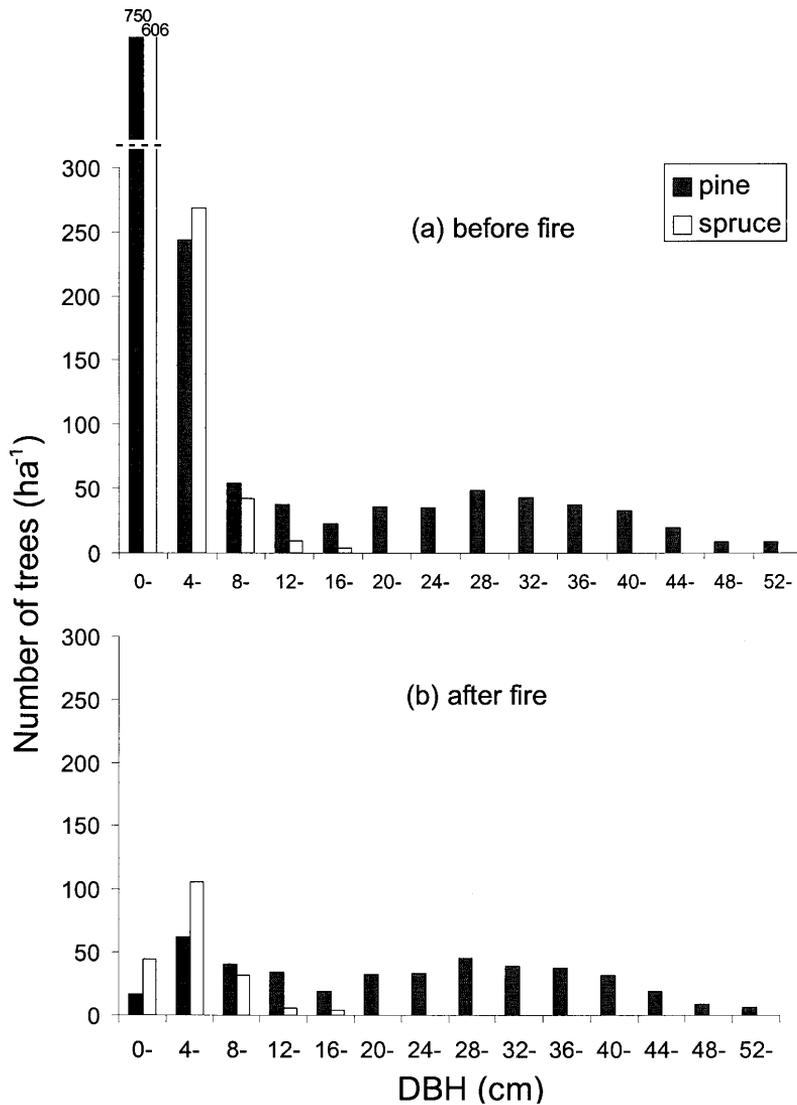


Fig. 5. Diameter distribution of living trees before (a) and after (b) the prescribed burning. The recorded numbers of living trees prior to the fire were: $n_{\text{pine}} = 1711$ and $n_{\text{spruce}} = 1155$.

The high mortality recorded among the largest trees contrasts with data from the earlier mortality studies mentioned above. This discrepancy could be due to the fact that the previous studies were done in habitats where fire affected managed or semi-natural forests, in which no old trees with open fire scars were present. Therefore, this phenomenon may have been over-

looked. Since such trees formed a major feature of the primeval forest landscape, we believe that this mortality pattern used to be a general characteristic of the boreal forest. This observation underlines the importance of studying truly natural forests, when trying to reconstruct ecological consequences of forest fires. However, our recorded mortality for the largest trees may have



Fig. 6. An old fire-scarred pine (DBH = 63 cm) that was hollowed out by the fire and eventually broke, Kåtaberget, Sweden 1995.

been higher than would generally be found in an old-growth stand because of the long time that had passed since the last fire (142 yr.). More frequent fires will increase the possibility for exposed wood to char, and may also induce fire-damaged trees to produce more resin, which would probably preserve them better from fungi and insects. Nevertheless, occasional intervals of this length were not rare in the boreal forest prior to fire suppression (Zackrisson 1977, Linder 1988, Niklasson and Granström in press), so we believe this mortality pattern needs careful consideration.

The structural changes caused by the prescribed burning also included a large reduction in the frequency of the smallest class of trees (Fig. 5), leading to a less dense understorey. However, in relation to the last fire, the effects on stand structure seem to be minor. A considerable number of spruces survived the burning, for example, in contrast to the fire in 1853, when no spruces on dry to mesic sites seemed to survive. The lower mortality caused by the prescribed burning is most likely a result of the low fire intensity, resulting from the high moisture content in the

finer fuel fractions. However, the number of spruces surviving the prescribed burn may have been overestimated. When the mortality was recorded, four months after the fire, some severely fire-damaged spruces in smaller diameter classes had a minor proportion of green foliage left and were recorded as living. These trees may have died in the next few years, i.e. the fire-induced mortality process may not have been entirely finished in October, when the data was collected. According to our field observations we believe this may slightly change the mortality figures, but not change the overall size-dependent mortality pattern.

As mentioned earlier, the fire in Kåtaberget appeared during relatively moist conditions, furthermore it was performed as a repeated strip burn. Consequently, the intensity was held low, and this particular fire may not be representative to the average natural forest fires. Therefore, it is likely that the average natural fire was of higher intensity, resulting in a generally higher mortality. However, fire intensity, fire spread and depth of burn have certainly varied, also in the primeval forest (cf. Schimmel 1993).

The prescribed fire resulted in a significant input of dead trees, showing that even low intensity surface fires can bring about considerable changes in stand structure. Downed logs, and especially large ones, are of great importance for a lot of wood inhabiting species including insects (Ahnlund and Lindhe 1992), fungi and mosses (Söderström 1988, Andersson and Hytteborn 1991, Aronsson et al. 1995, Bader et al. 1995, Larsson 1997). They are also important in a range of ecological processes such as nitrogen fixation and nutrient translocation between fungi and plants (Maser and Trappe 1984, Samuelsson et al. 1994). Thus, structural changes induced by such fires may have considerable ecological effects on the habitat.

We suggest that when prescribed burning is used for conservation purposes in the managed forest landscape (where fire-scarred pines are almost absent), it should be supplemented with a deliberate felling or girdling of large trees to create dead, large-diameter trees. The same recommendation could also be put forward when selective cutting is used to mimic the effects of forest fire on the tree layer. If snags are also absent, we recommend that such trees are created through girdling some years before a prescribed burning take place. In that way we may facilitate the genesis of charred stumps, which also were a characteristic feature of the natural forest.

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References

- Ahnlund, H. & Lindhe, A. 1992. Endangered wood-living insects in coniferous forests – some thoughts from studies of forest-fire sites, outcrops and clear-cuttings in the province of Sörmland, Sweden. *Entomologisk tidskrift* 113: 13–23.
- Ahti, T., Hämet-Ahti, L. & Jalas, J. 1968. Vegetation zones and their sections in north-western Europe. *Annales Botanici Fennici* 5: 169–211.
- Andersson, I. & Hytteborn, H. 1991. Bryophytes and decaying wood – a comparison between managed and natural forest. *Holarctic Ecology* 14: 121–130.
- Andersson, S.O. 1954. Funktioner och tabeller för kubering av småträd. *Meddelanden från Statens Skogsforskningsinstitut* 44: 1–29.
- Andrén, T. 1996. Skellefteskogen omkring 1761. *Skogshistorisk Tidskrift* 1996(6): 3–24.
- Angelstam, P. & Pettersson, B. 1997. Principles of present Swedish forest biodiversity management. *Ecological Bulletins* 46: 191–203.
- Arnborg, T. 1949. Från svedjebruk till hyggesbränning. Särtryck ur Norrlands skogsvårdsförbunds exkursionsprogram. Stockholm.
- Aronsson, M., Hallingbäck, T. & Matsson, J.-E. 1995. Swedish red data book on plants 1995. Swedish Threatened Species Unit, SLU, Uppsala. 272 p. (In Swedish, with English summary.)
- Bader, P., Jansson, S. & Jonsson, B. G. 1995. Wood-inhabiting fungi and substratum decline in selectively logged boreal spruce forests. *Biological Conservation* 72: 355–362.
- Berg, Å., Ehnström, B., Gustafsson, L., Hallingbäck, T., Jonsell, M. & Weslien, J. 1994. Threatened plant, animal, and fungus species in Swedish forests: distribution and habitat associations. *Conservation Biology* 8: 718–731.
- Brandel, G. 1990. Volume functions for individual trees. Swedish University of Agricultural Sciences, Garpenberg, Department of Forest Yield Research, Report 26.
- Byram, G.M. 1959. Combustion of forest fuels. In: Davis, K.P. (ed.). *Forest fire: control and use*. McGraw-Hill, New York. p. 90–123.
- Ehnström, B., Gärdenfors, U. & Lindelöw, Å. 1993. Rödlistade evertebrater i Sverige. Databanken för hotade arter, Uppsala. 69 p. (In Swedish.)
- , Långström, B. & Hellquist, C. 1995. Insects in burned forests – forest protection and faunal conservation (preliminary results). *Entomologica Fennica*

- nica 6: 109–117.
- Fries, C., Johansson, O., Pettersson, B. & Simonsson, P. 1997. Silvicultural models to maintain and restore natural stand structures in Swedish boreal forests. *Forest Ecology and Management* 94: 89–103.
- Granström, A. 1993. Spatial and temporal variation in lightning ignitions in Sweden. *Journal of Vegetation Science* 4: 737–744.
- 1995. Om skogseldens natur och eldkulturen i Sveriges skogar. In: Larsson, B. (ed.). *Svedjebruk och röjningsbränning i Norden*. Nordiska museets förlag. ISBN 91-71088-374-X.
- Hägglund, B. & Lundmark, J.-E. 1977. Site index estimation by means of site properties Scots pine and Norway spruce in Sweden. *Studia Forestalia Suecica* 138: 1–38.
- Hare, R.C. 1965. Contribution of bark to fire resistance of southern trees. *Journal of Forestry* 63: 248–251.
- Jonsson, P. 1997. 1995 års naturvårdsbränning av Kåta-bergets naturreservat – effekter på trädsnittet. SLU, Umeå, Institutionen för skoglig vegetationsekologi, Rapporter och uppsatser 10. ISSN 1102–6197.
- Kalabodakis, K.D. & Wakimoto, R.H. 1992. Prescribed burning in uneven-aged stand management of Ponderosa pine/Douglas fir forests. *Journal of Environmental Management* 34: 221–235.
- Kohh, E. 1975. A study of fires and hard pan in the forest of Älvdalen. *Sveriges Skogsvårdsförbunds Tidskrift* 73: 299–336. (In Swedish, with English summary.)
- Kolström, T. & Kellomäki, S. 1993. Tree survival in wildfires. *Silva Fennica* 27: 277–281.
- Larsson, K.H. (ed.). 1997. Rödlistade svampar i Sverige – Artfakta. (Swedish red data book of Fungi 1997.) Artdatabanken, SLU, Sverige. 547 p.
- Linder, P. 1988. Jämtgaveln – en studie av brandhistorik, kulturpåverkan och urskogsvården i ett mellannorrländskt skogsområde. Länsstyrelsen i Västernorrlands län, 1988:3. Härnösand, Sverige.
- , Elfving, B. & Zackrisson, O. 1997. Stand structure and successional trends in virgin boreal forest reserves in Sweden. *Forest Ecology and Management* 98: 17–33.
- Maser, C. & Trappe, J.M. 1984. The seen and the unseen world of the fallen tree. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, General Technical Report PNW-164. p. 1–56.
- McCarthy, E.F. & Sims, I.H. 1935. The relation between tree size and mortality caused by fire in southern Appalachian hardwoods. *Journal of Forestry* 33: 155–157.
- Niklasson, M. & Granström, A. in press. Numbers, size, and frequency. Long term trends in fires on a north-Swedish boreal landscape. *Ecology*.
- , Zackrisson, O. & Östlund, L. 1994. A dendroecological reconstruction of use by Saami of Scots pine (*Pinus sylvestris* L.) inner bark over the last 350 years at Sädvajaure, N. Sweden. *Vegetation History and Archaeobotany* 3: 183–190.
- Parviainen, J. 1996. The impact of fire on Finnish forests in the past and today. In: Goldammer, J.G. & Furyaev, V.V. (eds.). *Fire in ecosystems of boreal Euroasia*. p. 55–64.
- Peterken, G.F. 1996. *Natural woodland, ecology and conservation in northern temperate regions*. Cambridge University Press. 522 p. ISBN 0-521-36792-1.
- Pettersson, O. 1941. *Gamla byar i Vilhelmina I–IV*. (Faksimil 1982.) Kungliga Skytteanska Samfundets handlingar, Umeå.
- Samuelsson, J., Gustafsson, L. & Ingelög, T. 1994. Dying and dead trees – a review of their importance for biodiversity. Swedish Environmental Protection Agency, Report 4306. ISBN 91-620-4306-4.
- Schimmel, J. 1993. On fire, fire behaviour, fuel succession, and vegetation response to fire in the Swedish boreal forest. SLU, Umeå, Department of Forest Vegetation Ecology, Dissertations in Forest Vegetation Ecology 5.
- & Granström, A. 1996. Fire severity and vegetation response in boreal Swedish forest. *Ecology* 77: 1436–1450.
- & Granström, A. 1997. Fuel succession and fire behavior in the Swedish boreal forest. *Canadian Journal of Forest Research* 27: 1207–1216.
- Sepponen, P. 1989. Study on the forest fire in the Pisavaara nature reserve. *Folia Forestalia* 736. p. 80–85. (In Finnish with English summary.)
- Söderström, L. 1988. Sequence of bryophytes and lichens in relation to substrate variables of decaying coniferous wood in northern Sweden. *Nordic Journal of Botany* 8: 89–97.
- SPSS. 1993. *SPSS for Windows: Advanced statistics release 6.0*. SPSS Inc., Chicago, Ill.
- Stokes, M.A. & Smiley, T.L. 1968. *An introduction to tree-ring dating*. Chicago University Press, Chicago.

- SYSTAT. 1992. SYSTAT for Windows: Statistics, version 5 edition. SYSTAT, Inc., Evanston, IL.
- Tanninen, T., Storrånk, B., Haugen, I., Friis Möller, P., Löfgren, R., Thorsteinsson, I. & Ragnarsson, H. 1994. Naturskogar i Norden. Nord 1994:7. Nordiska Ministerrådet, Köpenhamn. 109 p. ISBN 92-9120-406-4.
- Viro, P.J. 1969. Prescribed burning in forestry. *Communications Institutii Forestalis Fenniae* 67. 49 p.
- Wardle, D., Zackrisson, O., Hörnberg, G. & Gallet, C. 1997. The influence of island area on ecosystem properties. *Science* 277: 1296–1299.
- Wikars, L.O. 1995. Clear-cutting before burning prevents establishment of the fire adapted *Agonum quadripunctatum* (Coleoptera: Carabidae). *Annales Zoologici Fennici* 32: 375–384.
- Zackrisson, O. 1977. Influence of forest fires on the north Swedish boreal forest. *Oikos* 29: 22–32.
- 1980. Forest fire history: ecological significance and dating problems in the North Swedish boreal forest. Proceedings of the fire history workshop, October 20–24, 1980, Tucson, Arizona. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-81.
- , Nilsson, M.-C. & Wardle, D. 1996. Key ecological function of charcoal from wildfire in the Boreal forest. *Oikos* 77: 10–19.

Total of 49 references