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NUMBERS AND SIZES OF FIRES: LONG-TERM SPATIALLY EXPLICIT FIRE HISTORY IN A SWEDISH BOREAL LANDSCAPE

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Abstract. The spatial display of fire over time on the landscape is ecologically important, and spatially explicit analyses offer a possibility of revealing anthropogenic influence on fire regimes. Nonetheless few such analyses have been attempted for longer time frames. We identified past fires in a northern Swedish boreal landscape using fire scars on *Pinus sylvestris* trees. Within a 19 × 32 km area, local fire chronologies were established at 203 points by cross-dating fire scars on 1133 wood samples, the earliest dating back to the 1100s. A total of 349 separate fires were identified to location and size. The estimated number of fires per unit area and time (after correcting for varying sample density over time) was relatively constant at 0.095 fires·$(10^4\ ha)^{-1}·yr^{-1}$ from 1350 to 1650. It increased gradually thereafter, except for a low period in the early 1700s, peaked at 1.17 fires·$(10^4\ ha)^{-1}·yr^{-1}$ in the mid-1800s, and then dropped dramatically after 1860. The proportion of the area burned per unit time also increased after 1650, in parallel with the increase in the number of fires (although much less strongly due to a counteracting trend in fire size), from an annual rate of 0.8% prior to 1650 to 2.8% in the mid-1800s. Prior to 1650, 90% of the total burned area was due to fires larger than 1000 ha, compared to 55% after 1650. This decrease in fire size with increasing number of fires may be an intrinsic property of the system: a negative feedback caused by lack of fuel in early succession. Fire intervals shorter than 15 yr were rare, and there was an increase in the hazard of burning during the first 3–5 decades after fire, suggesting an effect of fuel accumulation. Thus, the proportion of the area burned per unit time does not increase linearly with the number of fires in the landscape, because the probability that fires will stop at boundaries with recently burned areas increases over fires.

The changes in the number of fires per unit time mirror changes in the cultural use of the land, i.e., the gradual expansion of permanent settlements in the area after the late 1600s. They are not explained by changes in climate records. This suggests that the increase in fire numbers from the second half of the 1600s represents an increase in anthropogenic fires. Before 1650, the number of fires detected per unit area and time was only marginally different from the present-day density of lightning ignitions in the region (∼ 0.1 fires·$(10^4\ ha)^{-1}·yr^{-1}$), whereas during the mid 1800s it was 11.7 times higher.

These results show that large alterations in the fire regime can occur without substantial changes in the proportion of area burned per unit time, as exemplified by the trend after 1650, when there were concurrent changes in the number of fires and in average fire size. Therefore, the number of fire events per unit area and time should be an important variable in the analysis of fire history and its underlying causes.

Key words: anthropogenic fires; boreal landscape; dendrochronology; fire frequency; fire history, spatially explicit; fire regime; fire size; landscape ecology; Pinus sylvestris; *Swedish boreal forest.*

INTRODUCTION

The temporal and spatial patterns of fires are important variables at a landscape scale, because they determine the successional status, age distribution, and grain of the vegetation covering the landscape. There are, however, difficulties in describing past fires with sufficient spatial and temporal resolution. Analysis of charcoal in lake sediments or peat stratigraphies can provide records over millennia (MacDonald et al. 1991, Bradbury 1996, Clark and Royall 1996), but they do not provide spatial detail. Fire histories from tree-ring chronologies usually cover shorter time spans, but have the potential to resolve spatial patterns (Bergeron and Brisson 1990, Swetnam 1993).

To date, the focus of most fire-history studies in boreal areas has been on quantifying the amount of burned ground per time unit. Terminology varies, but this has been termed ''fire frequency at point scale'' (expressed as percentage annual burn [Johnson 1992]), ''average fire interval'' (at point scale), or ''fire cycle'' (time to burn the equivalent of the study area [Reed et al. 1998]). The term ''fire frequency,'' in particular, has been used with various meanings, so for clarity, we avoid these terms here and refer simply to the propor-

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tion of the investigated area that burned per unit time. Several workers have obtained such estimates from fire intervals in scarred trees (Zackrisson 1977, Romme 1982, Engelmark 1984). They can also be inferred from the distribution of age classes (time since last fire) across the landscape (Van Wagner 1978, Johnson and Larsen 1991, Johnson and Gutsell 1994, Reed et al. 1998). In regions where stand-killing fires are typical, this may be the only alternative, because there usually are no trees that survive to record successive fires as fire scars within the bole. A disadvantage with this technique is that only a relatively short time span is covered, because each new fire destroys evidence of past burns. Also, the spatial fire patterns are poorly analyzed over time, since only the youngest burns are detected *in extenso.*

The proportion of the area burned per time unit is the product of two variables: the number of fires (ignitions) per unit area per unit time, and the size of the individual fires. The same area burned can thus result from either a large number of small fires or a small number of large fires, which complicates the interpretation of fire history from records of area burned. Quantitative estimates of the number of past fires per unit area and time should help distinguish between anthropogenic and lightning-ignited fires, by offering a comparison with present-day lightning-ignition densities.

The spatial pattern of fire (size distribution and spatial arrangement) is an ecologically important variable, separate from area burned, because it determines the grain of the landscape and, thus, factors such as dispersal distances for colonizing organisms (Moloney and Levin 1996, Turner et al. 1997). Information on the pattern of fire in the landscape can be found for the present situation in boreal regions where fire still is prevalent (Payette et al. 1989, Johnson 1992), but to date there have been few attempts to analyze long-term patterns (Bergeron and Brisson 1990, Dansereau and Bergeron 1993).

Here we combine cross-dating of fire scars in dead wood and living trees with sampling in a dense grid over a large area to derive a record of the spatial extent of individual fires over an extended period in northern Sweden. At this western periphery of the Eurasian taiga, forests are dominated by *Pinus sylvestris*, *Picea abies*, and *Betula* spp. The interior of the northern Scandinavian peninsula was until the late 1600s inhabited by a small population of semi-nomadic Saami, subsisting on fishing, hunting, and small-scale reindeer herding (Aronsson 1991). During the 1700s and 1800s an increasing number of homesteads were established. In the mid-1800s the lumber industry gradually expanded into the area, and today the main land use is forestry. The area burned annually is now minute, but there are several studies showing that fire was important as late as the latter part of the 1800s (Wretlind 1932, Tirén 1937, Zackrisson 1977, Engelmark 1984). Thus, it would be expected that the fire history during the past several-hundred years has been dynamic. To analyze this we established a dense network of cross-dated tree-ring fire chronologies within a 608-km^2 forest landscape and mapped the extent of past fires. From this base we extract data to show concurrent changes over time in the number of fires per unit area and time, sizes of individual fires, and the resulting proportion of the area burned per unit time.

Materials and Methods

The study area

The study was done within 19 × 32 km study area in northern Sweden (area 608 km^2, centered at 63°56′ N, 18°48′ E), where we established a fine-scale network of 203 sample points for dating of past fire events (Fig. 1, Fig. 2). The river Lögde (Plate 1, Fig. 1) runs through the central part of the study area. Two other rivers of similar size border the area: the river Gide to the west and the river Öre to the east. There are numerous lakes, but most are small. They cover about 5% of the area. Peatlands are frequent in depressions and on flat ground and cover 12% of the area (Fig. 2). The topography is gently undulating for the most part, with elevation ranging from 200 to 500 m above sea level (Fig. 2, Plate 1).

The bedrock is dominated by granite and gneiss, with occasional outcrops of gabbro and diorite (Gavelin and Kulling 1955). Soils are podsolized, usually with a 3–10 cm layer of mor humus. The mineral soil is predominantly glacial till, stony, with fine sand as the dominant textural fraction. After the retreat of the ice of the last glaciation, about half of the area was below sea level. Due to isostatic uplift, the highest post-glacial seashore line is today 250 m above sea level. Below this elevation, there are some areas of sediment, particularly in valley bottoms, with texture ranging from coarse sand to silt (Granlund 1943).

The climate of the region is characterized by long winters and warm, short summers. Snow typically covers most of the area from early November to the middle of May, but with large variations due to elevation, aspect, and forest cover. Southern aspects are usually snow-free in early May, while on north- and east-facing slopes snow patches often last into early June. There are ~150 d/yr with an average daily temperature >5°C (Alexandersson et al. 1991). Average annual precipitation at Fredrika, just northwest of the sampling area (Fig. 1) is 541 mm, of which 36, 47, 83, and 65 mm falls in May, June, July, and August, respectively (Alexandersson et al. 1991). The annual average temperature at Fredrika is 0.6°C (6.6°, 12.3°, 13.9°, and 12.0°C for the months May through August, respectively).

The forest ground vegetation is mostly dominated by ericaceous dwarf shrubs (*Vaccinium myrtillus*, *V. vitis-idaea*, *Calluna vulgaris*, and *Empetrum herma-*

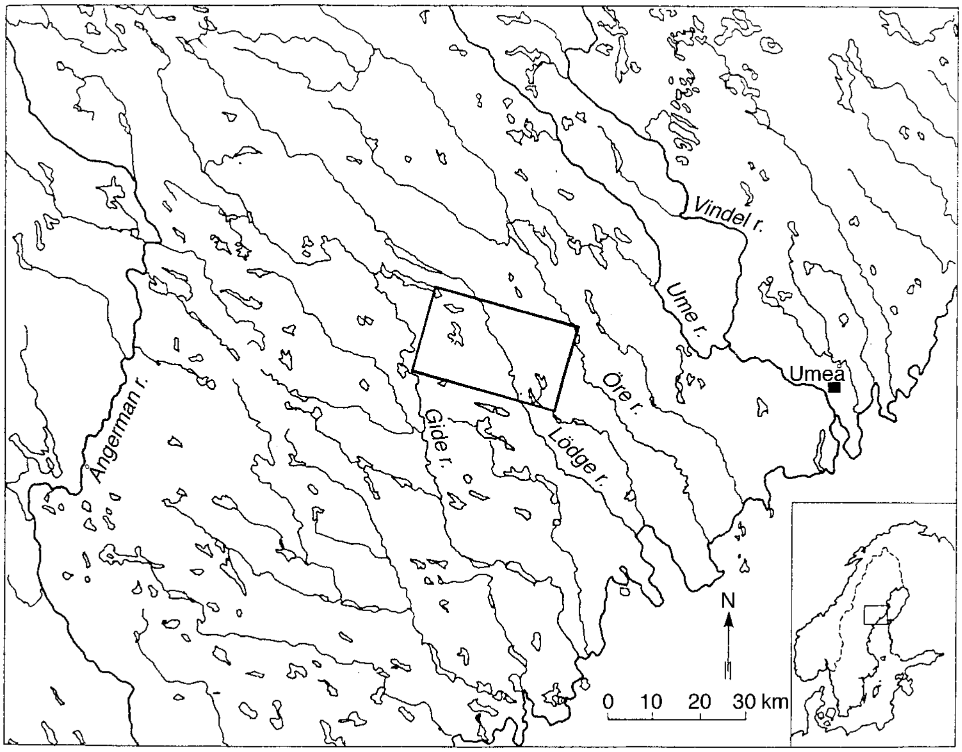

FIG. 1. Location of the study area in northern Sweden. Within the 19 × 32 km rectangle are 203 sampling points.

phroditum). The forest floor is covered by pleurocarpous mosses (*Pleurozium schreberi* and *Hylocomium splendens*) except for sandy sediments where *Cladonia* lichens are often dominant. In early succession after fire, various acrocarpous mosses increase in abundance, and a few species of herbs and grasses appear with the ericaceous dwarf shrubs (Schimmel and Granström 1996). Scots pine (*Pinus sylvestris* L.) and Norway

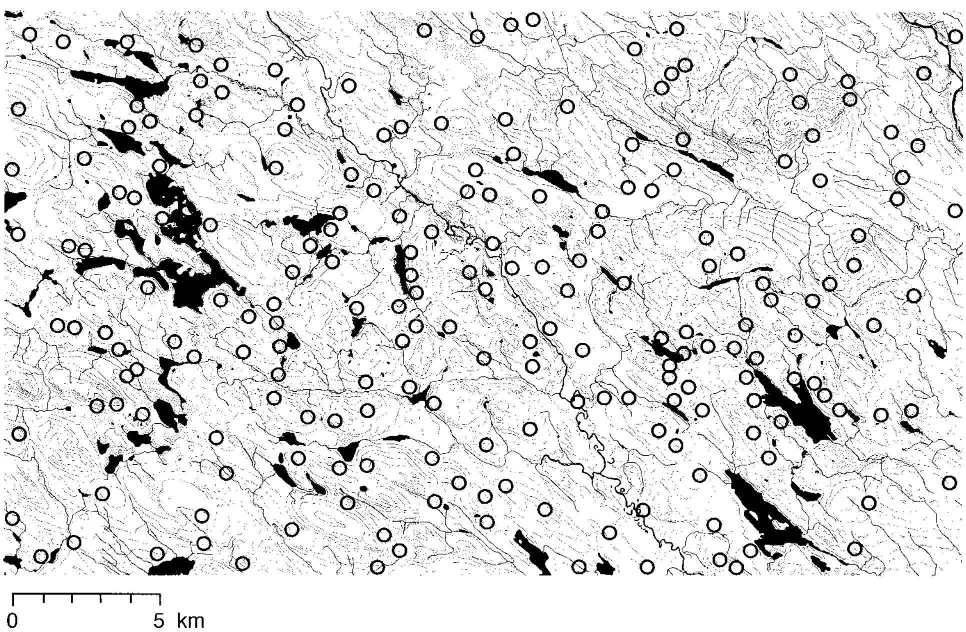

FIG. 2. Position of 203 sampling points (○) within the 19 × 32 km sampling area. Lakes are shown in black, and peatlands in half-tone. Contour lines are given for each 25-m increment in elevation.

PLATE 1. View toward the northwest over the forest landscape and Lögde river in the central part of the study area in northern Sweden. The river is an unregulated third-order river (Strahler 1957), which has cut a meandering channel through sandy sediments. The channel and unvegetated shore form a 30–50 m wide fuel break. In the valley bottom there are areas of peatland and seasonally inundated treeless grassland.

spruce (*Picea abies* L. Karst.) are the two dominant trees in the area. Scots pine is usually more abundant on dry soils and on nutrient-poor peatlands. On mesic and moist soils with a better nutrient status, such as slopes with northerly aspect and areas close to streams, spruce often dominates over pine. A slow-growing understory of spruce is found in all forest types, even on xeric sites. Among broadleaved trees, birches (*Betula pendula*, *B. pubescens*) are most common and are usually abundant in the first decades after clear-cutting or fire. Aspen (*Populus tremula*), sallow (*Salix caprea*), and alder (*Alnus incana*) are also found, but are rarely dominant.

The cultural history of the area is documented by Gothe (1948) and Lundkvist (1962). From prehistoric times up to the late 1600s, the area was inhabited by a sparse population of semi-nomadic Saami people. From the 1500s, and possibly earlier, people in agricultural villages close to the Baltic coast traveled into the area in summer to fish in the larger lakes. Between 1670 and 1685, a small number of homesteads was established, one of which was at lake Bjärten in the southeastern part of the study area. The colonization process continued and intensified from the mid-1700s, resulting in a dramatic increase in population density. As late as 1734 the population density in this region (later the parish of Bjurholm) was only 0.04 persons/km^2 (Lundkvist 1962). In 1800 it was 0.2 persons/km^2 and in 1884, 2.6 persons/km^2. People depended on animal husbandry and small-scale agriculture for sustenance until the late 1800s, when forestry expanded. Due to the harsh climate and unfavorable soils, the proportion of tilled land remained small. In 1820 it was about 0.1% (Lundkvist 1962).

Sampling

In order to reconstruct the sizes and shapes of past fires, we spaced sample points at ~2-km intervals. Several factors made sampling impossible at some locations. Wood collection for tar production (mainly in the late 1800s and early 1900s) and culling of fire-scarred trees by modern forestry has eliminated datable wood in some areas. Live *Pinus* trees and old wood were difficult to find at a small number of the more productive sites where *Picea* and deciduous trees were dominant. For these reasons, it was not possible to collect wood samples at fixed positions. Instead, we distributed sample points to obtain reasonable coverage of the entire area. In total, wood was collected at 203 sampling points (Fig. 2). Thus, each sampling point represents an area of ~3.0 km^2 (at an average distance of 1.7 km between points).

To obtain chronologies for as long a time period as possible and without hiatus, several wood samples were collected at each point. At every sampling point, we searched over an area of ~5000 m^2 for wood of Scots pine that could have recorded past fires. Living trees, snags, down logs, and stumps of different age were sampled with a chain saw. The sampling also included the completely surface-charred remains of very old natural stumps. Cross sections were taken from stumps and shorter snags. Partial cross sections were cut out from live trees and tall snags (see e.g., Arno and Sneck 1977). Material with no scars visible from the outside frequently contained overgrown minute fire scars and fire-induced disturbances in tree-ring morphology that were evident in the laboratory. All structurally intact samples were taken to the laboratory, regardless of whether they contained readily visible scars. A total of 1152 samples were collected (on average 5.7 samples per sample point), most of which had been repeatedly scarred by fire (on average 2.3 events per tree, range: 0–7). We obtained 147 samples from living trees and 1005 from dead wood.

To bridge hiatuses in chronologies, several sites were resampled after dating the first sampled material. An example of the construction of a chronology for one of the sites from living and dead material is given in

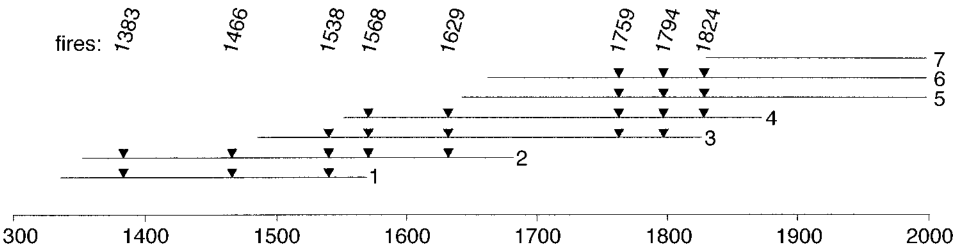

FIG. 3. Example of the construction of a chronology at one of the 203 sampling sites, from living and dead *Pinus sylvestris.* The triangles mark position in time of the fire indicators in the wood of the individual specimens. The trees often had life-spans of 300–500 yr and survived several fires. Postmortem preservation of the wood has sometimes extended 300 yr or more. Samples numbered 1, 2, and 3 are snags, whereas number 4 is a stump from a felled tree, and samples 5–7 are living trees.

Fig. 3. Wood from slowly growing trees with narrow rings proved resistant to decay. In several instances standing snags or down logs had survived 300 yr of exposure and two or three fires after their death without substantial loss of wood (Fig. 3). The oldest living pine we sampled was 530 yr old. Trees with a life-span of >500 yr were common in the dead-wood material.

Despite a systematic search for the oldest wood at each site, there proved to be large variations in the length of the chronologies, and, in a few cases, hiatuses could not be bridged (Fig. 4). Only 19 wood samples could not be cross-dated (see *Dendrochronology and cross-dating*, below), the remaining 1133 cross-dated samples span the time period from 1121 to the present. Sample points with chronologies extending back to the 1100s and 1200s are rare (Fig. 4), but 67 of the 203 points have chronologies extending to 1350, and 90 reach 1400.

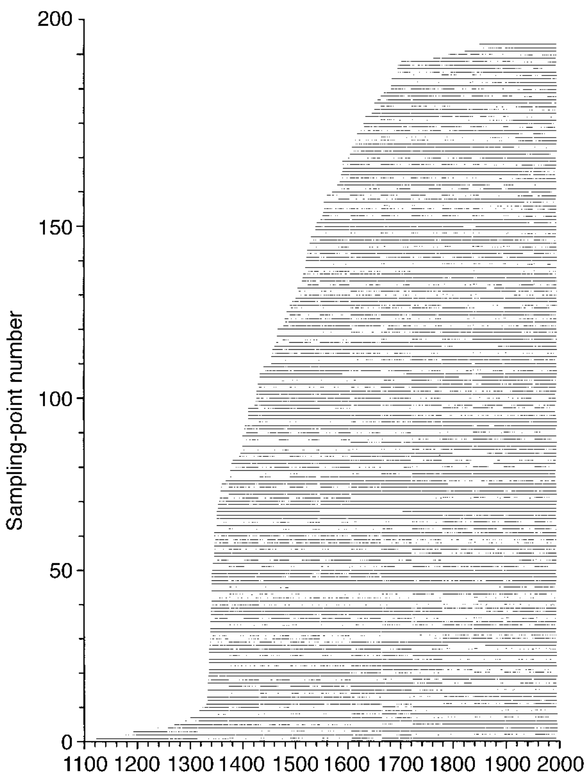

FIG. 4. Time span for the tree-ring chronologies at each of the 203 sample points within the 19 × 32 km study area in northern Sweden. Each chronology is based on several wood samples (on average 5.7 samples). A blank space indicates a hiatus in a chronology.

Not every fire is recorded in every tree. The scarring susceptibility is high for small, thin-barked trees and for trees that have been previously scarred. In fire-history work, trees are often considered as recording only after receiving their first scar (Baisan and Swetnam 1990). Here we consider the full chronology as recording for the following reasons. *P. sylvestris* trees with a diameter less than ~5 cm at ground level have thin bark and rarely survive fire (M. Niklassen and A. Granström, *personal observation*). This size often represents an age of 30–50 yr, during which the tree is a good recorder of *lack* of fire. For somewhat larger trees, the scarring susceptibility is high, should the tree survive. More problematic are large, un-scarred trees with thick bark, that may not record low-intensity fires. However, material sampled at each point typically includes a succession of trees with overlapping ages, thus minimizing this problem.

Dendrochronology and cross-dating

All wood samples were dried and sanded. Cross-dating was done under a dissecting microscope with 6–80 × magnification. A scalpel was used to expose a clean surface in critical areas, e.g. when determining the position of the fire lesion within a ring. Zinc paste was applied to increase contrast where needed. All samples were cross-dated using methods described by Douglass (1941) and Stokes and Smiley (1968), but with modifications for northern Swedish conditions (Niklasson et al. 1994). Many wood samples were discarded in the field due to insufficient number of intact rings for dating. Of the 1152 samples brought to the laboratory, a total of 19 (1.6%) could not be cross-dated, most of them due to the presence of compression wood.

In most cases fire scars were fully developed, i.e., the cambium had been killed in a portion of the tree circumference. In cases when there was no fully developed fire scar, fire-induced disturbances in the tree-ring morphology (Brown and Swetnam (1994) provided evidence for fire. Certain ring characteristics (heat-induced tracheid disturbance, traumatic resin ducts, etc.) have been found to be reliable indicators of fire damage in *Pinus sylvestris*, through repeated parallel observations of fully developed fire scars from the same fire event on other parts of the same tree or on neighboring trees (M. Niklasson, *unpublished data*).

Fire scars formed in the dormant period between two rings were assumed to be early fires (occurring before tree-ring growth had started), for several reasons. Experimental studies in this region have shown that fires occurring between ~15 June and 15 August can be detected in the ring formed in the year of the fire (A. Granström and M. Niklasson, *unpublished data*). The fire season typically starts in late May and ends in late August, but the climatic conditions rapidly become less conducive for fires during August due to the increasingly long nights, falling temperatures, and rising humidity. Lightning ignitions peak in late June and early July, with ~12% of all ignitions occurring prior to 15 June and only 3% after 15 August (Granström 1993). We therefore believe that only a minor proportion of the dormant-season fires detected in this study occurred after the cessation of radial growth, so we assigned dormant-season fires to the year when the first post-fire year-ring was formed.

Reconstruction of individual fire areas and proportion of the area burned per unit time

The fire years cross-dated at the different sample points permitted a reconstruction of the area of the individual fires. For large fires that spanned several sampling points, the borders were drawn halfway between neighboring recording and non-recording points. If a probable fuel break (peatland, lake, or watercourse) occurred between two such points closer to the recording point than the nearest non-recording point, the border was drawn along the fuel break. For fires dated at only one point and not at the surrounding points, the border was drawn at half the distance to the nearest non-recording point in all directions, but never farther than 1 km from the fire-recording point. If a probable fuel break (see above) occurred closer than 1 km from the point, the border was drawn there. The individual fires were delineated on a 1:50 000 map and their area was measured with a video surface-area meter. Open water falling within the delineation was discounted, but mire and swamp forest were not. Mires and swamp forests sometimes burn, depending on vegetation type, season, and severity of drought. For simplicity we included these areas when calculating burn area (mires cover in total 12% of the 19 × 32 km area and swamp forest less than 2%).

To compute the proportion of the area burned per unit time, we divided the number of sample points that burned in a particular year by the number of sample points active that year. By active points we mean those for which we have tree rings that could have recorded a fire (see Fig. 4). This value (the fraction of points burned per year) was taken as the proportion of the entire area burned per year. Data are presented as a running cumulative curve, but also as averages for periods covering a number of years. We could, instead, have entered the area for each fire estimated from the map analysis, but we believe that the error would have been larger, because borders are difficult to delineate correctly, particularly for the smaller fire fields. This might lead to a systematic bias in the estimates between different time periods.

To supplement our fire-scar record for the modern fire regime, we interviewed older residents in the area. They provided information on fires started by lightning and humans during the last few decades within ~10 000 ha of the study area. The lightning ignitions reported amount to an ignition density of 0.1 ignitions$\cdot$(10^4 ha)$^{-1}\cdot$yr^{-1}. All of these fires were controlled at a small size (mostly <1 ha). Several cases of prescribed burning after cutting were also documented, particularly for the period 1940–1960. These prescribed fires will be analyzed elsewhere and are not included in the data presentation.

Estimating number of fires and hazard of burning

The number of fires that are detected with point sampling within an area depends on the density of sample points, given that not all fires have been large enough to contact at least one sample point. Thus, our sampling should underestimate the number of small fires, because they sometimes fall between sample points—and the degree to which this happens should vary over time, as the number of active sample points varies. To arrive at an estimate of total number of fires occurring in the area, we applied a procedure correcting for undetected fires. If we assume that fires occur randomly across the landscape, and that our sample points are randomly distributed, the probability that a fire of area A will go undetected (i.e., intersect no sample points) is the zero category of a Poisson distribution $e^{-\lambda A}$, where λA is the Poisson parameter, λ being the number of sample points divided by the total area. Detection probability is the complement $1 - e^{-\lambda A}$. For example, with 203 sample points within our 57 760 ha area (excluding open water), the detection probability is ~0.3 for fires of 100-ha size and increases to 0.9 for fires of 700 ha. The assumption that our sample points conform to a Poisson distribution may be reasonably correct. When distributing a large number of quadrats onto the map of sample points we obtained a variance/mean ratio of 0.7 for the 203 points (indicating a slight overdispersion) and a ratio of 1.2 for the 132 points active in 1499 (indicating a slight aggregation).

To obtain an adjusted estimate of the total number of fires per unit area over time (accounting for undetected fires), we scaled each fire according to both the number of active sample points at that particular point in time and the size distribution of fires. In this procedure we used the two different size distributions we observed (one prior to 1650 and one post-1650). To arrive at an average correction factor for each number of sample points, we multiplied the detection probability for fires of each size class of 100 ha by the proportion of fires observed in that same size class. We used the detection probability of the center of each class (e.g., 150 ha for fires in the 100–200 ha size class), except for the first class, for which we used the detection probability of 100-ha-sized fires. This may be an underestimation, but we chose this conservative correction due to lack of detailed data on the size distribution for very small fires. We apply this estimation only for the period after 1350, because by then we have a reasonable number of sample points. The net effect is that a fire occurring in, e.g., 1400 is multiplied by 4.04, a fire in 1700 by 2.49, and a fire in 1850 by 2.51.

As a second approach for comparing number of fires between different time periods, we selected all points with chronologies extending beyond 1499 and covering the full period to the present and extracted the number of individual fires occuring here, without attempting any correction. This subset of sample points amounted to 120, i.e., 59% of the total. As indicated above, these detected fires may only account for a portion of all fires that have occurred in the landscape. However, any differences between time periods should be without bias, because they are based on the same sampling points. Thus, we avoid assumptions regarding the size distribution of fires and the random location of fires and sample points. The null hypothesis that the number of detected fires per unit time did not differ between an early time period (1499–1650) and a late one (1651–1870), was tested using chi-square analysis. The two time points used for dividing this material (1650 and 1870), were selected post hoc. From the latter part of the 1600s there was a marked increase in number of fires per unit time, and from 1870 there was a rapid decline.

For the same subset of 120 sampling points, the intervals between successive fires were calculated. This was also done for two separate time periods: pre-1650 and post-1650. The hazard of burning, i.e., yearly probability of a new fire in relation to time since the previous fire, was estimated from this set of intervals using the Lifetable routine of SPSS (Norušis 1993). The time span between the last fire before 1650 and the year 1650, at each sample point, was treated as a censored case for the early period. The same was done for 1870 for the late period. In these analyses, censored cases are included in the population at risk (Lee 1980). The null hypothesis that the survival function (i.e., the cumulative "loss" due to fire in relation to time since last fire) did not differ between the two periods was tested using the Wilcoxon-Gehan statistic (Norušis 1993).

Results

We detached 349 separate fires within the area, the first of which occurred in 1232. It was recorded at one site where the oldest wood sample had tree rings back to 1121. The second-oldest fire, at another site, was dated 1292. It is not possible to delineate the area of these early fires, due to the low number of chronologies reaching that far back (Fig. 4). At 66 of the sampling points, the oldest dateable wood was from pines that had piths dating 1330–1360, indicating a major fire a few years earlier (38 of these points dated 1330–1340). At 5 of the 10 points where the chronologies reached back earlier than 1330, there was a fire early in the season of 1328. These five sites are well separated, and we believe that the 1328 fire covered ~35 000 ha of the 60 800-ha sample area, as indicated by sites at which the oldest material was recruited in the period shortly after 1328 (Fig. 5).

From ca. 1350 the sampling points are numerous enough to show the spatial pattern of fires in some detail. The sampling points with records of a particular fire are typically located adjacent to one other, and rarely are unburned points surrounded by burned ones, which makes the reconstruction of the burned areas straightforward. In Fig. 6 the delineation of a fire in 1499 is given as an example, showing the points recording and not recording that particular fire.

Within the 60 800-ha sample plot there have been no absolute fire breaks. For example, some fires have stopped against the Lögde river, which runs through the center of the plot (Plate 1), but others apparently jumped it (Fig. 6).

The 349 fires are presented as cumulative numbers over time (Fig 7, lower curve). This is an underestimation of the true number of fires on an area basis, because small fires have a low detection probability in the point sampling. The correction procedure using the observed size distribution for fires and the detection probability for different-sized fires under different numbers of sample points provides an estimate of the number of fires over time for the period 1350–1997 (Fig. 7, upper curve). There is an acceleration until the late 1800s, but, within this general trend, several distinct periods can be discerned: a relatively constant number of fires per unit area and time in the 1300s, 1400s, 1500s, and early 1600s (0.095 fires$\cdot$(10^4 ha)$^{-1}\cdot$yr^{-1} until 1650), an increase from the second half of the 1600s, interrupted by a period from 1698 to 1730 with low numbers (0.11 fires$\cdot$(10^4 ha)$^{-1}\cdot$yr^{-1}), a relatively constant rate during 1730–1840 (0.58 fires$\cdot$(10^4 ha)$^{-1}\cdot$yr^{-1}), a peak in the period 1840–1860 (1.17 fires$\cdot$(10^4 ha)$^{-1}\cdot$yr^{-1}) and finally a sudden drop from around 1870 (Fig. 7).

An alternative approach for analyzing trends over time is to use data only for sites covering the full period

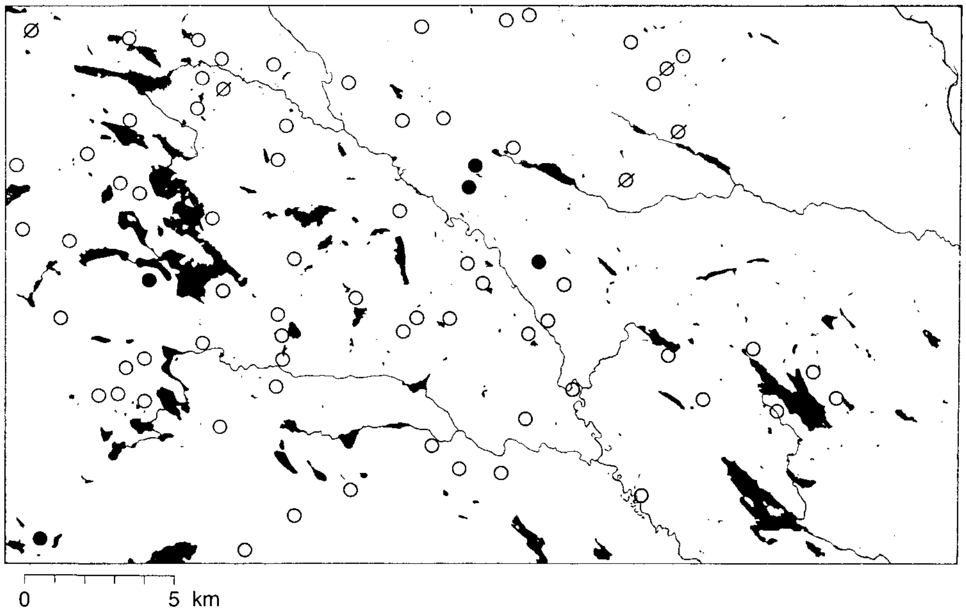

FIG. 5. Sample points with fire-scar evidence for a fire in 1328 (●) and points where the oldest wood was from trees with piths dating between 1330 and 1360 (○), which we presume were established as a result of the 1328 fire. A Ø symbol denotes points with chronologies predating 1328 that lack evidence of the fire.

from 1499 to the present (Fig. 4). Due to the smaller sample, the number of detected fires is lower, but the same pattern appears, with distinct trends in the number of detected fires per unit time (Fig. 8a). Comparatively few fires occur up to the mid-1600s and in the early 1700s. Then follows a gradual increase culminating in the 1800s, and low numbers since the late 19th century. Comparing the period 1499–1650 with 1650–1870 for this restricted data set, the number of fires per unit time was 2.9 times higher in the later period ($P < 0.001$, chi-square analysis). The difference is reflected partly in large numbers of fires occurring in certain years, but even more in the proportion of years with a detected fire. In the early period, 21% of the years had one or

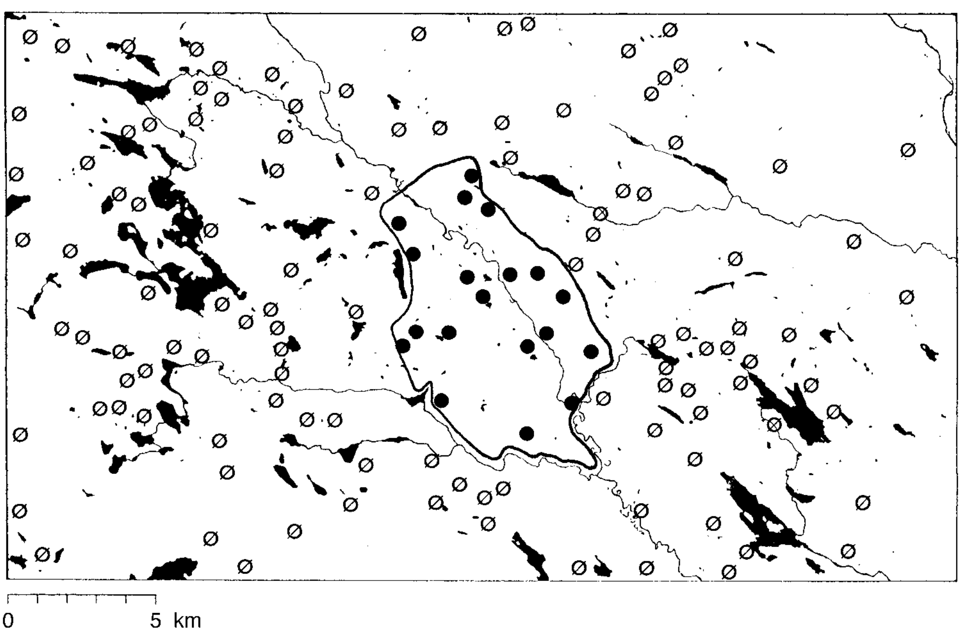

FIG. 6. Example of the delineation of an individual burn. This fire burned in 1499; ● symbols denote points with fire-scar evidence for the fire and Ø symbols denote points with tree rings unaffected by the fire in 1499.

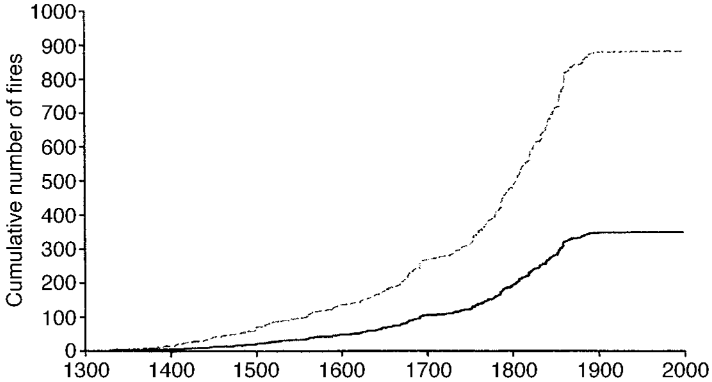

FIG. 7. Cumulative number of fires within the 19 × 32 km sample area. The lower line gives the observed numbers. The upper line gives the estimated number of fires on the landscape. This estimate was based on detection probability for burns of different size under different numbers of sample points and the size distribution of the observed fires. This estimate commences in 1350, when there were 68 active sample points.

more detected fires, compared to 52% of the years in the later period. Between 1831 and 1860, 80% of the years had a detected fire.

Thus, in the period from the mid-1300s into the 1600s, fires were comparatively few, but several of them were large. There is a trend towards diminishing size over the full time period (Fig. 9). The size distributions of the detected fires for the two periods, 1499–1650 and 1651–1870, are both highly skewed towards small fires. The log cumulative distribution of fires over log fire size (Fig. 10) indicates similar relationships between size and numbers for the two populations, but with a higher proportion of large fires in the early period. In the later period there was only one fire larger than 10 000 ha (in 1652), and the three largest fires during the post-1650 period all occurred prior to the year 1700 (Fig. 9), emphasizing the trend of diminishing fire sizes. The differences in size and numbers are exemplified in Fig. 11 where all detected fire areas are given for one early 50-yr period (1499–1548) and one late 50-yr period (1799–1848).

Although the proportion of fires larger than 1000 ha was only 23% in the early period and 6% in the later period (Fig. 10), a large part of the total burned area is nevertheless due to large fires. In the early period 90% of the fire area was burned in fires larger than 1000 ha, vs. 55% in the later period.

The proportion of the area burned per unit time changes over time (Fig. 12), although less than would be observed if the average area of burns remained constant, i.e., an effect of the counteracting trend in fire size. The area burned was ~0.8%/yr prior to 1650, it increased to an average of 1.4%/yr for the period 1650–1870 and then fell abruptly to <0.25%/yr for the last three decades of the 1800s. During the peak period, 1830–1860, on average 2.8% of the area burned per year.

The intervals between fires at a given sample point varied from 9 to 350 yr (Fig. 13). For fire intervals prior to 1650, the median interval was 79 yr, compared to 52 yr for fire intervals after 1650 (Fig. 13). For both time periods, fire intervals shorter than 20 yr are rare. The cumulative survival function, i.e., the proportion of freshly burned area remaining unburned over time, differed substantially between the two periods (Fig. 14). The null hypothesis, that survival was equal during the two time periods, was rejected ($P < 0.0001$, Wilcoxon-Gehan). The low number of cases with very short intervals between fires results in a hazard of burning (probability of fire as a function of time since the last fire) increasing gradually during the first ~50 yr for the early period and ~30 yr for the later period (Fig. 15). For ages over ~50 yr, there is no obvious trend for either time period, but the hazard remain much higher for post-1650 than for pre-1650. The scatter is large, due to the rapidly diminishing number of cases at higher ages. The number of cases drops below 100

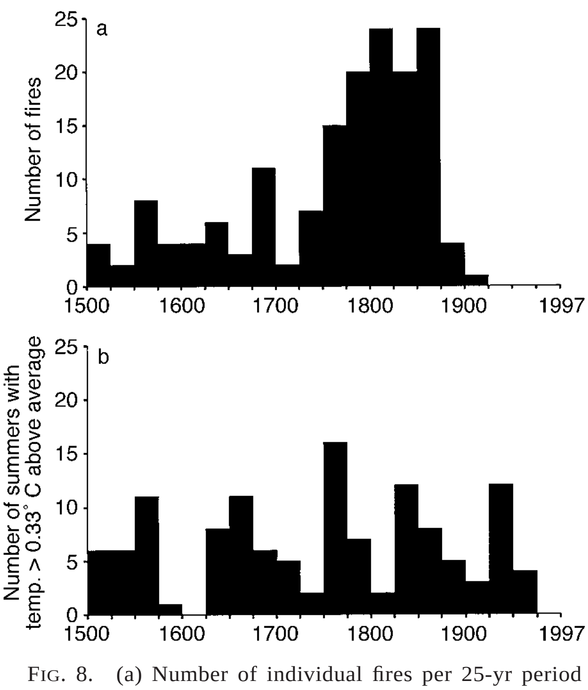

FIG. 8. (a) Number of individual fires per 25-yr period detected at the 120 sampling points with chronologies covering the full period since 1499. (b) Number of summers per 25-yr period with >0.33°C summer temperature anomaly in climate reconstructions by Briffa et al. (1990). There are no data for the period 1975–1997.

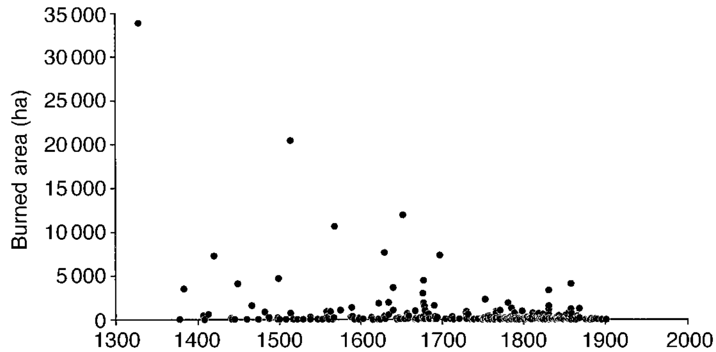

FIG. 9. Size of all detected individual fires over time (mid-1300s and following) in the northern Sweden boreal study area.

at an age of ~135 yr for the early period and at 75 yr for the later period.

DISCUSSION

Our study provides the first long-term spatially explicit reconstruction of fires for a boreal landscape, although there have been several observations over shorter time frames (Foster 1983, Payette et al. 1989, Dansereau and Bergeron 1993). Unlike earlier analyses of fire history, using fire-interval data (Zackrisson 1977) or reconstructions based on time since last fire (Johnson and Larsen 1991), we are able to analyze the numbers of fires per unit area and time as well as their size, not just the resulting area burned. The general picture emerging is of an early period ending in the mid-1600s with relatively few fires in the landscape, some of which were very large, followed by a period of greatly increasing numbers of fires that were progressively smaller in size. Finally, from around 1870, there was a dramatically decreasing number of fires.

Climate and human factors

The causes behind these long-term changes in the fire regime could potentially be climatic, anthropogenic, or both. Climate change could act on both the number of fires (through an altered density of lightning ignitions) and on the size of individual fires (through different weather conditions prevailing during the burning sessions), both of which would influence the proportion of the area burned per unit time. Climate change has been inferred to have altered the fire regime in several studies in North America (Clark 1990, Johnson et al. 1990, Bergeron 1991, Johnson and Larsen 1991, Swetnam 1993). In our material there is no obvious correlation with known trends in regional climate. The best proxy climate data available for the region are summer temperature reconstructions based on tree-ring data from Torneträsk, 500 km north of our area (Briffa et al. 1990). Years with large temperature anomalies in the Torneträsk area appear to coincide with warm summers in boreal Fennoscandia (Briffa et al. 1990). If the observed changes in the fire regime were driven by climate, such major trends should be evident in the Torneträsk data. But we observe neither short-term nor long-term trends that could explain the large increase in number of fires during the 1700s and 1800s. The average summer temperature for the period 1500–1650 was only marginally lower (0.05°C) than for the period 1651–1870 (data in Briffa et al. 1990). The proportion of years with a positive summer temperature anomaly >0.33°C (compared to the average temperature in 1951–1970) was 21% in the early (pre-1650) period and 30% in the later (post-1650) period. When comparing 25-yr periods from 1500 onwards, there are large differences both in the number of observed fires and in the number of years with large pos-

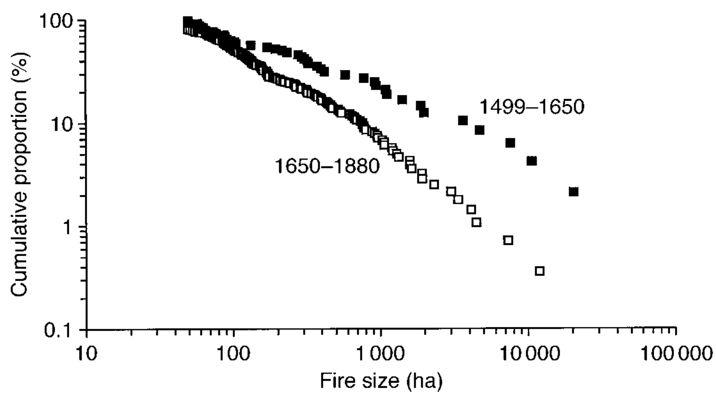

FIG. 10. Cumulative size distribution of all detected fires for the two time periods 1499–1650 and 1650–1880. Fires smaller than 50 ha have been lumped together. Note the logarithmic scales on both axes.

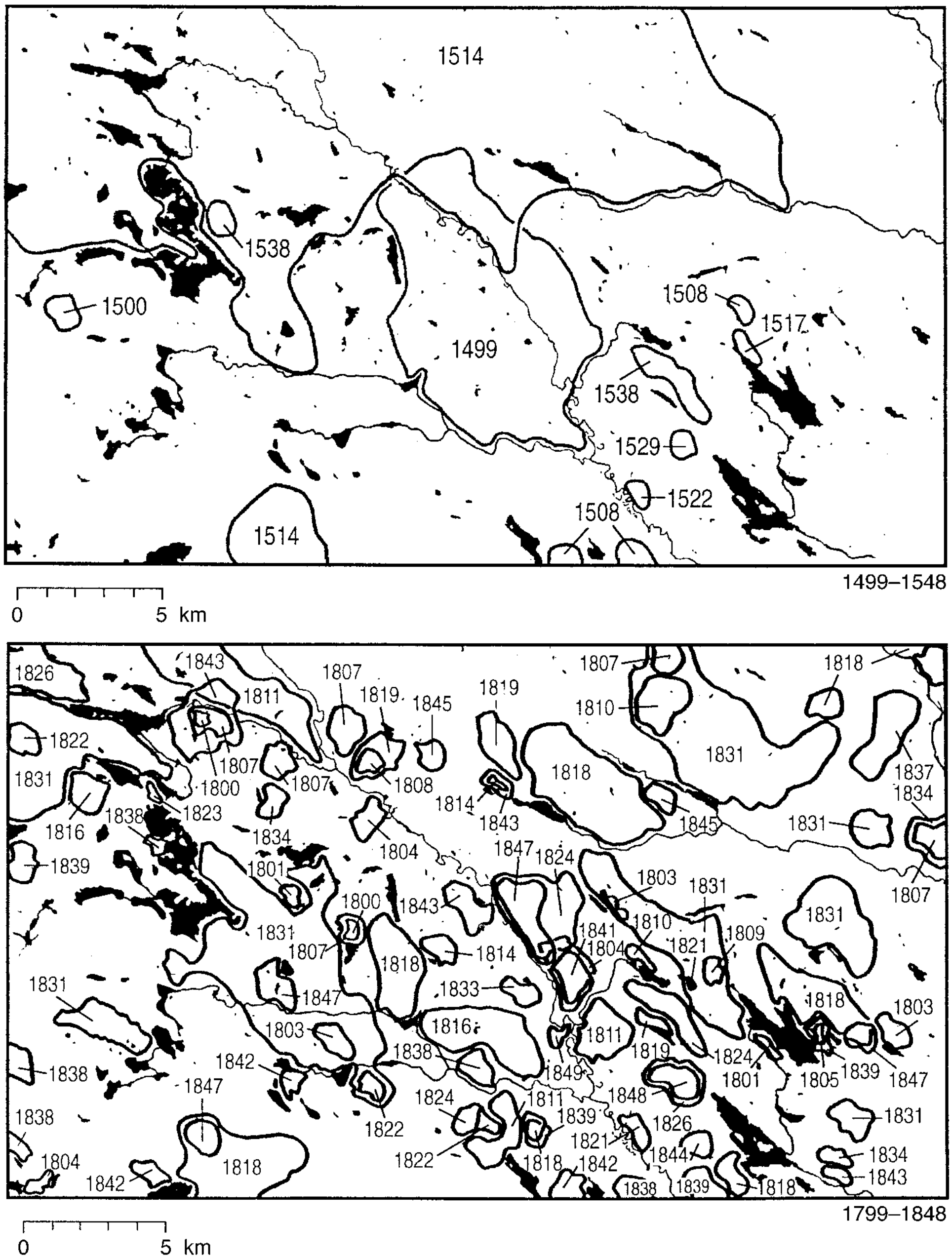

FIG. 11. Individual fires illustrated for two different time periods, each covering 50 yr. Lakes and larger streams are indicated on the maps for reference.

itive temperature anomalies (Fig. 8b), but no correlation between the two variables (correlation coefficient 0.2, P = 0.4 for the period 1500–1875).

Documented changes in the human population and utilization of the area coincide better with the observed trends in the fire regime than does climate. Before 1670 this area was inhabited by a small number of the Saami people, subsisting on fishing, hunting, and reindeer herding. Although the number of herded reindeer was low prior to the 1600s (Aronsson 1991), it is widely assumed that the Saami were careful in their use of fire (Laestadius 1833, Wretlind 1934), because reindeer depend on the slowly regenerating ground lichens (Sarvas 1937) for winter forage. The colonists who settled around 1670–1680 (or possibly somewhat earlier, although the legal deeds give 1670 as the first date of settlement) were not numerous (three settlements in an area of ~ 1200 km^2), but their use of fire was extensive according to early accounts (Lundkvist 1962). They too depended in part on fishing and hunting, but they also raised cattle, sheep, and goats, and engaged in small-scale agriculture, including slash-and-burn techniques

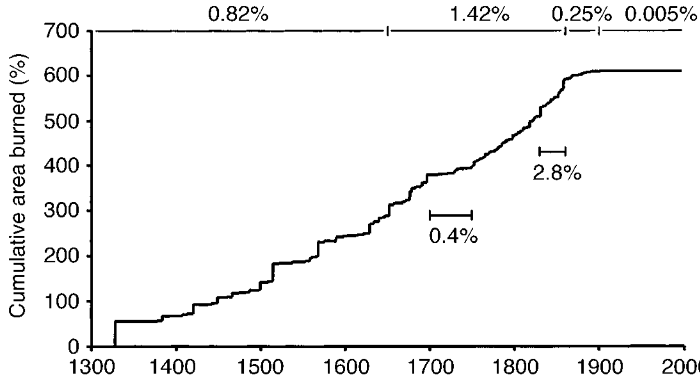

FIG. 12. Cumulative burned area over time in terms of percentage of the study area. Estimates of area burned in each year were based on the proportion of sample points recording fire out of the total number of active sample points for that particular year. (For the first major fire, in 1328, the area burned was instead estimated from the spatial reconstruction illustrated in Fig. 5.) The average percentage of the total area burned per year is indicated on the horizontal line at the top for various periods.

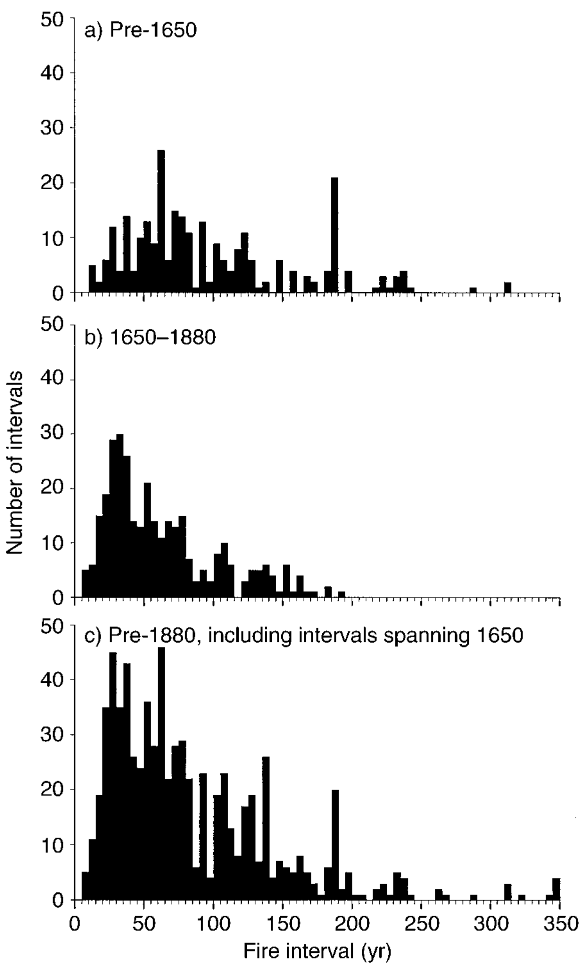

FIG. 13. Distribution of fire intervals (length of time betweem fires). (a) Intervals formed prior to 1650 (n = 275 intervals). (b) Intervals formed between 1650 and 1880 (n = 327 intervals). (c) All intervals pooled, including intervals spanning the year 1650 (n = 724 intervals). Only the fire intervals observed at the 120 sample points with chronologies reaching beyond 1499 are included.

(Lundkvist 1962). In the early part of the 1700s, war and numerous conscriptions in the agriculturally developed areas near the Baltic coast resulted in a recession that affected the whole region. Not until ca. 1740 were new settlements started again, as part of a colonizing process that accelerated through the 1700s and 1800s. Thus, the increase in the number of fires per unit time in the late 1600s, the low numbers in the first three decades of the 1700s, and the dramatic increase thereafter all coincide with documented trends in the cultural use of the area, which should influence the fire regime.

In the period 1350–1650, the numbers of fires on a time and area basis are not greater than figures that could be expected from lightning ignitions. At present the density of lightning ignitions in boreal Sweden averages 0.05 ignitions$\cdot(10^4\ \mathrm{ha})^{-1}\cdot \mathrm{yr}^{-1}$ (Granström 1993). It may be somewhat higher in this area, because the average value includes both coastal areas and areas near the western mountains where ignitions from lightning are rare (A. Granström, *unpublished data*). Our interviews (see: *Materials and methods: Reconstruction of individual-fire areas and . . .* ,) yielded an ignition density of 0.1 ignitions$\cdot(10^4\ \mathrm{ha})^{-1}\cdot \mathrm{yr}^{-1}$. This compares with an estimate of 0.095 fires$\cdot(10^4\ \mathrm{ha})^{-1}\cdot \mathrm{yr}^{-1}$ on average for the period 1350 to 1650. Not all lightning-ignited fires grow to substantial size, even in the absence of control, so these figures suggest that anthropogenic fires may have played some role even in this early period. It is conceivable that the slight increasing trend in the number of fires over the period 1300–1650 (Fig. 7) is due to increased human activities in the area, e.g., summer fishing expeditions to lakes in the interior (Lundkvist 1962). For the peak years 1840–1860, we detected 56 fires, which is 4.6 times the present level of lightning ignitions per unit area and time (assuming the value of 0.1 ignitions$\cdot(10^4\ \mathrm{ha})^{-1}\cdot \mathrm{yr}^{-1}$). The estimated total number of fires (corrected for undetected fires), amounts to 11.7 times the present lightning-ignition density. Thus, there is good evidence for predominantly anthropogenic fires in this period. It could be argued that the time period for which we have estimates of lightning-

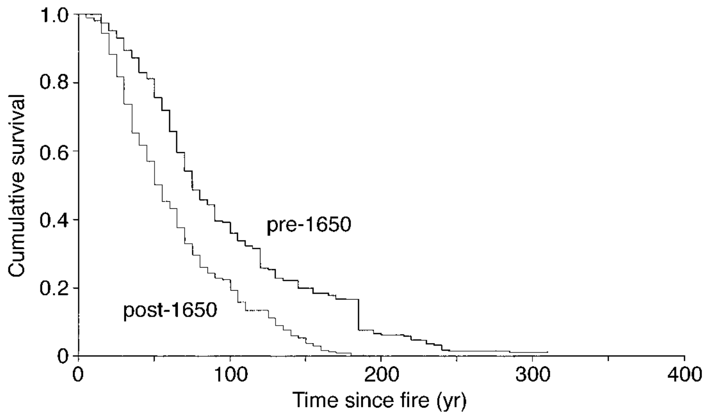

FIG. 14. Estimated survivorship curves pre-1650 and post-1650, i.e., the proportion of freshly burned area remaining unburned over time.

ignition densities (the last 50 yr for the interviews and 1953–1975 for data in Granström [1993]) is unrepresentative, but Briffa et al. (1990) do not suggest this period to be below a long-term average in temperature.

We believe that the anthropogenic fires in the later period are due to several different activities such as burning for improved cattle grazing, escape fires from slash-and-burn plots, and carelessness with campfires. The paucity of written accounts makes it difficult to assess their relative contributions, but in the 1800s, when cattle herds were large (Lundkvist 1962), it is likely that much burning was deliberate to improve the grazing. Informants in the area verified one such case as late as 1895 (J. Norberg, *personal communication*). Around 1850 large-scale timber exploitation reached the area (Tirén 1937, Östlund et al. 1997), and in the 1860s state forests were organized, with increased efforts at fire prevention and enforcement of fire regulations. Deliberate burning probably ceased gradually (Wretlind 1934, Tirén 1937), and the interest in suppressing fires, both lightning-ignited and anthropogenic, increased. Today fire suppression is highly effective. According to informants in the area, no fires have escaped beyond a few hectares during the last 50 yr, although there have been several ignitions, due to both lightning and carelessness.

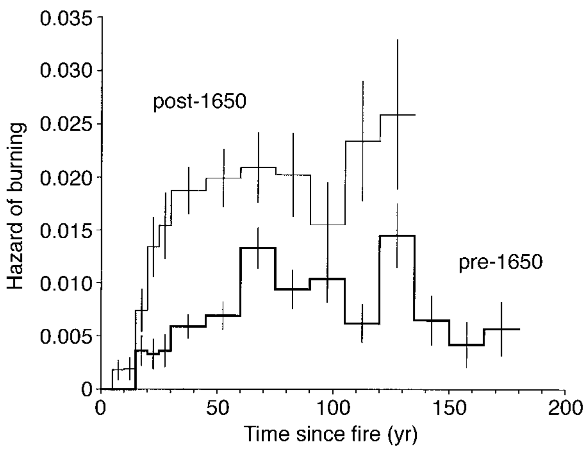

FIG. 15. Estimated hazard of burning, or yearly probability of a new fire with increasing time since the last fire (5-yr classes up to the class 30–35 yr, thereafter 15-yr classes). The vertical lines indicate ±1 SE. Data are for the two periods 1499–1650 and 1650–1880. For the pre-1650 period, 409 cases are exposed to risk for the first 5-yr class, and 61 cases for the last class shown (165–180 yr). For the post-1650 period, there are 449 cases for the first class, and 40 cases for the last class shown (125–140 yr).

Sampling the fire regime

Certain criteria have to be met for a long-term spatially explicit reconstruction to be possible. Fires must not generally be stand replacing, and the wood must be resistant to decay after the individual tree has died. For vast segments of the boreal forest, particularly in North America, fires generally are stand replacing (Johnson 1992), which precludes this type of analysis. Further, the spatial scale of sampling should be relatively fine and the area large in relation to the size of fires, in order to reveal the spatial pattern of fires. Nevertheless, there are still biases inherent in our sampling with regard to both the number of fires on an area basis and their size. Many small fires undoubtedly escape a point-sampling network, and the corrected values for numbers per unit area and time rest on assumptions of size distribution of the smallest fires, for which we have little knowledge. Precision in these estimates would increase with an increasing density of sample points, but this gain must be weighed against the need to cover a sufficiently large investigation area. Also, our main goal was to uncover trends over time rather than absolute levels, and these should be robust, particularly when only using data from the full-length chronologies (Fig. 8).

Our estimates of the proportion of the area burned per unit time should not be systematically affected by the density of sample points. There may be a bias in that our sample does not include, e.g., swamp forest, due to lack of datable wood. However, such areas are only minor fragments in the landscape—and again our intention was not primarily to get an unbiased estimate for this district, for comparison with other regions. Instead we wanted a comparison over time, and here there should be no bias, since we were able to follow the same sample points through time.

Fire-regime feedbacks and consequences

The number of fires per unit area and time increased 10-fold between the period 1350–1650 and the mid-1800s (1840–1860), whereas the proportion of the area burned per unit time increased only 4-fold, due to the counteracting trend in fire size. We can see two factors contributing to this. First, if we assume that the additional fires were anthropogenic, they may have involved a larger proportion of days with low-severity burning conditions, with low spread rates and therefore smaller final size. In contrast, lightning ignitions are typically associated with severe fire weather (Kinnman 1936, Nash and Johnson 1996). Second, the data strongly suggest that recent burns, up to an age of 15–20 yr, have acted as fire breaks. This is shown in a progressive increase in the hazard of burning (Fig. 15) and also in the many occasions when a burn directly borders a slightly older burn (M. Niklasson and A. Granström, *unpublished data*). Fuel analyses in *Vaccinium myrtillus*-type forests in northern Sweden (Schimmel and Granström 1997) have shown that steady-state conditions in the fine fuel on the ground are reached 30–50 yr after fire. In vegetation up to 10 yr old, fire spread is marginal or zero even during severe fire-weather conditions (Schimmel and Granström 1997). These relations would result in a negative feedback between the number of fires in the landscape and the total area burned, with an upper possible level for the latter at ~5% of the area burned annually (given a 20-yr regeneration time for the fuel). The rate of burning in the period 1830–1860 would have come close to this situation had it continued for longer, with nearly 3% of the area burned annually. Conversely, with an increasing proportion of the area burned per unit time, there will be an increased proportion of aborted ignitions, due to fuel shortage. This effect should be proportional to the amount of the landscape that is in early succession and therefore would have been more important in the later period (i.e., would tend to reduce the difference in number of fires pre- and post-1650).

The data provide good evidence for a shift in size distribution between the early and late periods, which should be even greater than the change shown by the distributions of reconstructed fire sizes (Fig. 10). This is because many of the larger fires of the early period were not completely contained within the 19 × 32 km study plot, and small fires (of which there is a larger proportion in the later period) are underrepresented. Still, for both time periods the log cumulative frequency distribution over log fire size are nearly linear, particularly for size greater than ~700 ha (which should not be affected by the sampling bias of the point sampling (see *Materials and methods: Estimating number of fires and . . .*). This is in agreement with observations from other regions (Malamud et al. 1998) of exponential fire-size distributions.

At the landscape level there are ecological consequences of the two variables, number and size, which are separate from those of the resulting area burned (Swetnam 1993). When fires are few but large (as prior to 1650), distances between recent fire-fields will be larger and the ''fire-free'' periods in a given-size landscape will be longer than when fires are many but small (as in, for example, the 1800s)—even if the total area burned happens to be similar. This leads to greatly altered dispersal distances for organisms that need to colonize recently burned areas through migration, such as fire-dependent insects (cf. examples in Evans [1971]). It also implies an altered patch size for animals such as the moose (*Alces alces*), which utilize particular age classes of vegetation (Bergström and Hjeljord 1987, Cederlund and Okarma 1988).

The data suggest that fires have been relatively small compared to other regions, even before 1650. In boreal Canada and parts of Siberia much larger fires have been frequently observed (Payette et al. 1989, Stocks et al. 1996). The reasons for the comparatively smaller fires in our area need further analysis, but may relate to differences in both landscape structure (cf. Dansereau and Bergeron 1993) and climate.

Our results show that estimates of the number of fires per unit time and area are important for long-term analyses of the fire regime and interpretations of the underlying causes of change. Sometimes the average fire interval can show a signal of change (Veblen et al. 1999), but due to the fuel feedback it may well be that number of fires is the more sensitive indicator. For reasonable estimates of the number of fires per unit time and area, the sampled area must be at a scale above or at least close to the scale of the larger fires. A constant amount of burned ground per unit time (expressed as a percentage of the area burned per unit time, fire cycle, or average fire interval) does not necessarily imply a constant fire regime. Conversely, an altered amount of burned ground per unit time may be due to changes in either the number of fires per unit area and time or in their average size, or both. When there are very large changes in the number of fires, the cause is likely to be anthropogenic rather than due to climatic change.

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