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A long-term record of *Quercus* decline, logging and fires in a southern Swedish *Fagus-Picea* forest

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Abstract. We reconstructed forest development and disturbance events (fire and logging) during the last 1000 yr with tree-ring data, pollen and charcoal analysis from a semi-natural *Fagus sylvatica-Picea abies* forest (ca. 1 km^2) in the hemiboreal zone. According to pollen analysis, *Quercus robur* together with *Pinus sylvestris* was abundant in the forest until the turn of the 18th/19th centuries when these species disappeared completely (*Quercus*) or nearly completely (*Pinus*) and were replaced by *Fagus* and *Picea*. The disappearance of *Quercus* was corroborated by the remarkable discovery of a single *Quercus* stump that had been cut in the 18th century and had become overgrown and preserved by a very old *Picea*. In total 11 fires were dated from 1555 to 1748 from fire scars in several *Pinus* stumps cut 100 - 200 yr ago. Since the last fire in 1748, no *Quercus* or *Pinus* have regenerated in the core of the reserve apart from single pines in neighbouring managed forest (80 yr ago). During the period of documented fires *Fagus* was protected from fires in a refuge made up of large boulders. *Picea* colonized the region at the time when the fires ceased 250 yr ago. We hypothesize that most of the fires were probably of human origin because of their patchiness and high frequency compared to the natural background levels of lightning ignitions in the region. On a 300-yr time scale, logging and fire suppression seem to strongly overshadow the effect of climate change on forest composition and dynamics.

Keywords: Charcoal; *Fagus sylvatica*; Hemiboreal zone; Old-growth forest; Paleo-ecology; *Picea abies*; *Pinus sylvestris*; Pollen; *Quercus robur*; Tree ring.

Nomenclature: Tutin et al. (1964-1976).

Abbreviation: LID = Lightning Ignition Density.

Introduction

Knowledge of past disturbance regimes is largely lacking for the vast European hemiboreal zone (*sensu* Ahti et al. 1968), situated between the boreal zone to the north and the nemoral zone to the south. Here, broad-leaved trees, e.g. *Quercus robur*, *Fagus sylvatica*, mix with conifers such as *Picea abies* and *Pinus sylvestris* (Nilsson 1997). Fires, as inferred from sedimented charcoal and recent tree-ring analysis, have been common in areas not subject to strong oceanic influence (Tolonen 1985; Vuorela 1986; Bradshaw & Hannon 1992; Mitchell & Cole 1998; Lindbladh et al. 2000; Niklasson & Drakenberg 2001). In general, most northern European broad-leaved trees are regarded as relatively fire-sensitive (Nilsson 1997), except perhaps for oaks (*Quercus robur* and *Q. petraea*), whose thick bark may give some protection from fires. Several North American oaks (*Q. rubra* and *Q. alba*) with similar ecology and habitat requirements are regarded as fire-adapted by some authors (Abrams 1992) although contradictory opinions exist (e.g. Clark 1997). *Q. robur* is more common today along the east coast than in the west of southern Sweden and pollen records indicate that this was also the case in the past (Björse & Bradshaw 1998; Lindbladh et al. 2000). This distribution may reflect some degree of adaptation to climate and/or fire which both have large differences from east to west, which is manifested in the higher level of lightning ignitions in the east (Granström 1993).

However, human impacts on past fire regimes cannot be neglected when studying past disturbance regimes in Europe. Strong indirect evidence of early human use of fire for managing the environment is shown by abundant charcoal in sediment located in areas under oceanic influence where natural ignitions are rare (Hannon et al. 2000). Historical accounts confirm extensive human use of fire in southern Sweden since at least the 17th century up to the early 20th century, both for improving heathland and for slash and burn agriculture in forests (Malmström 1939; Weimarck 1953; Larsson 1989). Fire management of *Calluna* heathlands occurred across large areas in western Europe until recently (e.g. Atlestam 1942; Gimingham 1972; Odgaard 1994; Goldammer et al. 1997); the human use of fire in these heathlands is well understood relative to forest ecosystems in central, western and eastern Europe.

The Siggaboda Reserve consists of an old-growth, mixed *Fagus sylvatica* and *Picea abies* stand with documented high conservational value, mainly as a result of old living or dead *F. sylvatica* trees (Nilsson et al. 1995; Arup et al. 1997). The reserve is surrounded by managed conifer dominated forests with little or no conservational value. According to a pollen analysis, *Quercus* was abundant in the Siggaboda Reserve until the end of the 18th century, but disappeared completely at the beginning of the 19th century, being replaced by *Picea* and *Fagus* (Björkman & Bradshaw 1996). Björkman & Bradshaw (1996) suggested that the establishment of *Fagus* was connected to fire and that *Picea* was favoured by climatic change (i.e. Little Ice Age).

Findings of large, moss covered cut stumps of *Pinus sylvestris* (Niklasson pers. obs.) triggered a renewed interest in this forest after Björkman & Bradshaw's (1996) pollen study was published. These observed stumps suggest that human disturbances may have played a large role in the recorded changes in the past. Our hypothesis is that human disturbances (e.g. logging and dramatic shifts in fire regime) catalysed the rapid changes recorded in the pollen analysis. The shift from deciduous species to *Picea* dominance is a recurrent feature from many southern Swedish pollen records during the last millennium (e.g. Björkman 1997; Björse & Bradshaw 1998; Lindbladh et al. 2000), but the dynamics behind this development is poorly understood. To test this hypothesis, we conducted an extensive tree-ring investigation of remnant old trees and remains of wood from stumps. We applied tree-ring methods to reconstruct past tree dynamics, for detecting the presence/absence of fires and to calibrate and perhaps re-evaluate the stand scale pollen and charcoal analysis of Björkman & Bradshaw (1996). The methods of tree-ring analysis and traditional large basin pollen analysis are usually effective at very different spatial (stand vs regional) and temporal scales (decades to centuries vs centuries to millennia). However, theory predicts (Jacobson & Bradshaw 1981; Bradshaw & Webb 1985; Prentice 1985; Sugita 1994) that the technique of stand scale pollen analysis (*sensu* Bradshaw 1988) used in the Siggaboda Reserve reflects a much smaller area and is at a higher spatial resolution when compared to large basin pollen analysis. This resolution allows it to be linked with tree-ring methods and the combination of these methods could broaden our perspective of the past forest dynamics and successional patterns.

Material and Methods

Study area

Siggaboda Reserve is located at Stensjönäs, southern Småland (56°28' N; 14°34' E), at the southern edge of the hemiboreal zone of southern Sweden (Ahti et al. 1968).

The reserve lies on the border between the counties of Skåne and Blekinge, which prior to 1658 formed the border between Sweden and Denmark (all dates are years AD). Mean annual precipitation is 700 mm.yr^{-1}. The mean annual temperature is ca. 6 ºC; the mean July and January temperatures are 15 ºC and –3 ºC, respectively (Raab & Vedin 1995). The bedrock is granitic gneiss covered by moraine, very rich in boulders in many places.

The old-growth forest core of Siggaboda Reserve occupies ca. 5 ha and was set aside as a reserve in the 1940s. A buffer zone was established outside the core area in 1995, giving the reserve a total area of 70 ha. The core area is dominated by an uneven-age mixed forest of *Fagus sylvatica* (ca. 60 % of total basal area) and *Picea abies* (ca. 40 %), with the oldest individuals of both species being ca. 250 yr old. In recent decades, gaps have opened the canopy and permitted regeneration of both species. However, the dominant trees are very similar in their stem and crown characteristics, indicating uniform age. *Betula pendula* and *Alnus glutinosa* occur in low numbers. *Pinus sylvestris* is very rare in the core area (only two mature specimens are present but very old, moss-covered, large diameter *Pinus* stumps, typically 35 - 60 cm in diameter were recently discovered throughout the reserve (Niklasson pers. obs.). *P. sylvestris* regeneration is essentially absent from the reserve. Massive boulders up to ca. 5 m in diameter are conspicuous features, particularly in the core area of the reserve. The numerous boulders make the canopy sparse with many small openings, which create suitable microclimatic conditions for much of the rare invertebrate fauna and epiphytic lichen flora of the old-growth *Fagus* forest (Nilsson et al. 1995). The understorey is sparse, with *Vaccinium myrtillus* as the dominant species. The moss layer is prominent; on dry-mesic ground *Hylocomium splendens* and *Pleurozium schreberi* dominate, while on wetter ground *Polytrichum* species form thick carpets without herbaceous vegetation. The diverse beetle and lichen fauna includes many threatened species (Nilsson et al. 1995; Arup et al. 1997) mainly associated with large old or dead *Fagus* trees. Few, if any, signs of recent human disturbance can be found in the core area.

The buffer zone consists largely of two sown, nearly pure *Picea abies* stands, 80 and 115 yr old. The stands were actively managed until 1995. *Betula pendula*, *B.*

pubescens, *Pinus sylvestris* and *Salix caprea* make up the remaining ca. 10 % of the tree species composition. Isolated *Fagus sylvatica* individuals of either the same age or considerably older than *P. abies* are also encountered in this area.

Traditionally, farms in southern Sweden were organized into 'inäga' (in-field), which consisted of cultivated and mowed lands immediately surrounding the dwellings, and 'utmark' (out-land), which were less suitable for cultivation and were primarily used for grazing of domestic animals. The 'utmark' was typically forested, although slash and burn cultivation was common, particularly from the late 17th to the early 19th century (Weimarck 1953; Larsson 1980). The forest under study was classified as 'utmark'according to cadastral maps from 1868 and 1907.

Field methods

We analysed the tree age structure in the old-growth *Fagus-Picea* stand in the 5-ha core area (Fig. 1, below). Because permission for extensive sampling of increment cores was not granted, we selected one 157 m^2 (7.07 m radius) and one 314 m^2 (10 m radius) circular plot for analysis of the age structure of the dominant oldest trees. All trees (n = 19) in the plots were cored at the lowest height possible, 20 - 30 cm above ground. Only cores with pith or pith within 10 mm were accepted for further analysis. No seedlings or saplings were present on the plots. Increment cores were extracted from the only two *Pinus sylvestris* trees present in the core area; these two individuals were 50 - 70 m from the pollen sampling site (Fig. 1). As our goal was to maximize the information over the longest time possible, we also cored at six locations one of the dominant and oldest *Fagus* trees to obtain information on the earliest possible regeneration periods. To date possible traces of early fellings or disturbances we also removed wedge or disc samples (n = 24) of large diameter *Pinus* stumps throughout the entire reserve with a chain saw. All samples were dried and sanded to a smooth surface with a belt sander. In total, age data from 50 trees and stumps were collected in the reserve. To detect presence/absence of fire in the soil, we also searched for macroscopic charcoal in test pits (n = 3) and uprootings (n = 7) at ten locations distributed evenly across the core area. Here, we carefully examined the topsoil of fresh uprootings (1 - 2 m^2, 0.06 m^2 for test pits) for charcoal discernible by the eye (fragments typically larger than 3 mm). We only brought the charcoal fragments found and not the soil to the lab. The charcoal was identified under a microscope with the aid of the key by Schweingruber (1990). Conifer wood charcoal was not distinguished to species.

Tree-ring analysis and cross dating

Ring counts of *Fagus* and *Picea* and cross dating of *Pinus* was carried out under a microscope with up to 50 × magnification. In most cases all rings were clearly visible and thus ages are considered accurate to within 5 years. No age addition was made to correct for coring height, thus all ages are slight underestimates. All samples of *Pinus* were cross dated using a local chronology of pointer years according to methods described by Douglass (1941) and Stokes & Smiley (1968). Supporting pointer years also came from two cross dated fire history studies (Niklasson & Gustafsson 1999; Niklasson & Drakenberg 2001), 150 and 170 km east and northeast of the study area, respectively. For dating purposes and establishing the local pointer year chronology, a large number of samples from *Pinus* trees were sampled in the buffer zone and on a fresh clear cut outside the reserve (data not presented). Examples of useful pointer years were: 1598 (very wide and dark), 1618 (narrow), 1632 (narrow), 1690 (narrow), 1701 (narrow), 1756-1759 (strong growth decline), 1779/1780/1781 (very wide/narrow/wide rings), 1802 (narrow) and 1868 (narrow).

Pollen record

The pollen data used in this study is from the previously published work of Björkman & Bradshaw (1996). The basin they sampled for the pollen and charcoal analysis is located in the central part of the reserve core (Fig. 1). The basin is an isolated *Sphagnum* covered hollow, ca. 10 m diameter, entirely covered by tree crowns of surrounding *Fagus*, *Picea* and a few *Betula* trees (Björkman & Bradshaw 1996). The 'relevant pollen source area' for this kind of hollow has been shown by theory and observation to be no more 100 m in radius (Jacobson & Bradshaw 1981; Sugita 1994; Calcote 1995; Jackson & Kearsley 1998). Given that the large majority of the investigated trees or stumps were located in the reserve core area, it is likely that the information obtained from tree-rings and deposited pollen reflect a similar spatial scale.

We compared the tree-ring data with the pollen percentages of the key species from the pollen analysis (Björkman & Bradshaw 1996; see also Björkman (1996) for a complete pollen diagram). Björkman & Bradshaw (1996) obtained five radiocarbon dates from the profile, four from the last 1000 years. To facilitate the comparison with the tree-ring data, we calibrated the five radiocarbon years to calendar years using the OxCal program (Stuiver et al. 1993) (Table 1).

Results

Wood remains of Quercus and other tree species

Quercus is currently represented in the core area by a small number of seedlings and saplings, dispersed into the area from oaks around settlements some distance away. Remains of older *Quercus* were found at two locations. First, large charred wood fragments (0.5 - 1 cm) were retrieved from an old fire place at the edge and underneath a large boulder just outside the eastern border of the reserve in a *Pinus*/*Picea* dominated stand. The fireplace was not covered by vegetation due to extremely dry, rain protected conditions under the boulder. The fireplace was partially covered by weathered gneiss that had fallen down from the inner wall of the boulder. The charcoal fragments were confirmed to be from *Quercus* and conifer species (*Pinus sylvestris* or *Picea abies*). The fragments were not radiocarbon dated but should be at least a few hundred years old as they were mixed with the topsoil and not visible on the surface.

The second finding was unexpected. We discovered a large *Quercus* stump (65 cm diameter, *Quercus robur* or *Q. petraea* at the edge of the core area (Figs. 1 and 2, Plate 1). We did not attempt to determine the exact species due to reported minute or absent differences in wood anatomy (Schweingruber 1990). The stump was overgrown by a *Picea abies* individual. Apparently, the overgrowing *Picea* had preserved the stump by creating drier conditions, because no *Quercus* wood remained outside the stem and root perimeter of the *Picea*. We cored the *Picea* at the base and the pith was dated to 1815. A sample from the *Quercus* stump was cross-dated against *Quercus* master chronologies from this region (sample # 75380, Dendrochronological Laboratory, Lund University). The oldest ring was from 1550 and the youngest from 1738. Since a large portion was missing in the centre of the stump, we estimate that the germination had taken place much earlier than 1550, somewhere between 1400 and 1480. It had initially grown very slowly (radial growth ca. 0.7 mm per year), but a strong growth spurt occurred ca. 1700. Although the youngest rings and the bark had decayed, we estimate that the tree had been living until at least 1750 since there were no traces of sapwood (ca. 15 rings; Hans Linderson, Dendro-lab. Lund pers. comm.). Fol-

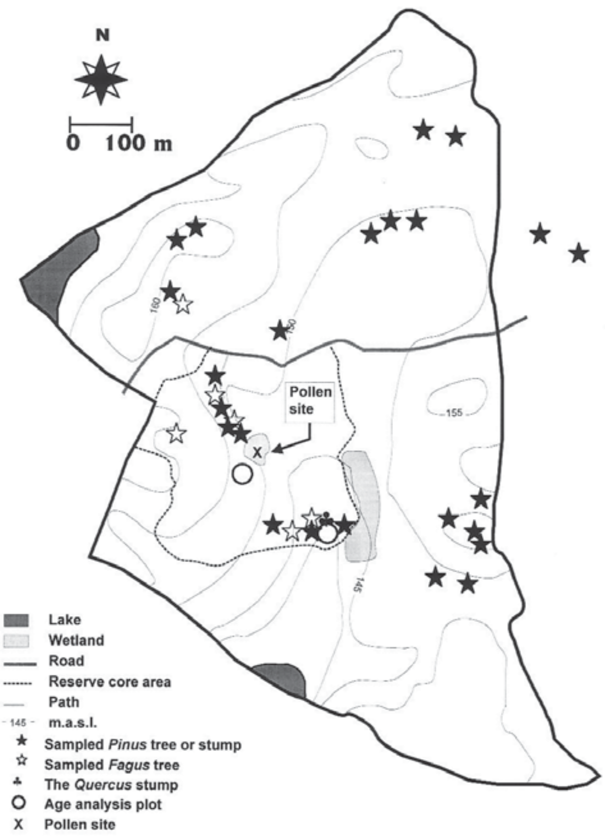

Fig. 1. Map of the Siggaboda Reserve showing the location of the sampled trees and the two circular age analysis plots.

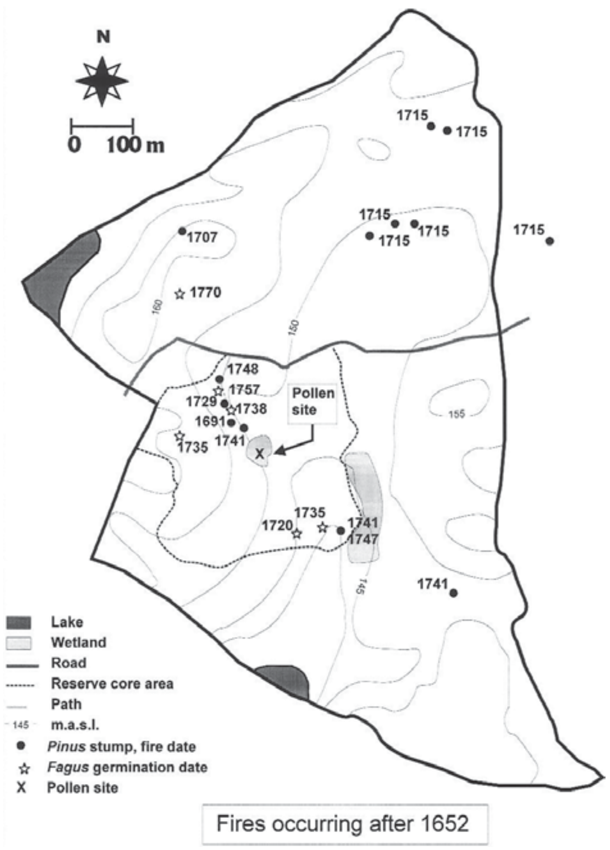

Fig. 2. Map of the Siggaboda Reserve showing the location of the trees or stumps affected by fires after 1652.

lowing this reasoning, the tree was cut between 1750 and 1815. We tentatively assign the cutting date to ca. 1780, a date well supported by the history of surrounding trees. Two nearby *Fagus* individuals showed growth spurts in 1782 and 1786; a third *Fagus* showed sign of a sudden change in environmental conditions by an abrupt growth suppression in 1780. One *Picea* individual located a few m from the stump had germinated a few years prior to 1787.

Fires

We found and dated fire scars in pine stumps at several locations (Fig. 1). The fire-scar record consists of 11 fires and extends from 1555 to 1748. The inferred fire history is presented as follows.

Post 1652 fires

Northeast of the core area, where large boulders are less common, a large fire took place in 1715. It was dated in six locations, covering an area of ca. 5 ha. North of the core area, a single fire scar was also dated to 1707. In the core area, we found a complex and patchy pattern of small burns (< 0.5 ha each, from 1691, 1729, 1741, 1747 and 1748) (Fig. 2). The presence of young fire sensitive *Fagus* trees during this period that regenerated as early as the 1720s is strong evidence that the fires only covered small areas. Clearly, some of the fires above did not affect the patches of what would have been young and small (2 - 8 cm diameter) *Fagus* trees. No fires were detected after 1748 in the stump material, even though many of the stumps had rings well into the 19th century. However, slash and burn cultivation, or slash burning as a silvicultural practice for regenerating some of the current 100-yr old forest stands, cannot be ruled out.

Table 1. Calibrated radiocarbon dates from the Siggaboda Reserve. Age range probabilities shown in parentheses. For those cases with alternatives (29.5 and 89.0 cm) we chose as the calibrated age the centre point of the age range with the largest probability.

Sample depth (cm)	^{14}C age (yr BP)	Calibrated age (calendar yr)	Calibrated age max-min 68.2% confidence
29.5	150 ± 60	1800 1720-1880 (0.68) 1910- (0.15)	1670-1700 (0.17)
42.0	330 ± 70	1560	1480-1640
56.7	460 ± 50	1440	1410-1470
72.0	940 ± 80	1090	1010-1170
89.0	2120 ± 60	140 BC 230-50 BC (0.82)	360-310 BC (0.18)

1652 fire

In 1652 a major fire covered most of the reserve, including the core area. Two scars were dated to this year in the eastern part of the reserve. In two other locations strong growth disturbances, typically associated with fire, were noted. For an extensive review of this indirect dating method see Brown & Swetnam (1994) and Niklasson & Granström (2000). Ten of the sampled *Pinus* stumps had regenerated shortly after this fire (1665-1680) at several locations, including the core area. All show very rapid initial growth, typical of *Pinus* regenerating under open conditions. It is likely that the 1652 fire initiated this cohort of *Pinus* as no other fires were recorded between 1623 and 1691.

Plate 1. The preserved *Quercus* stump and the overgrowing *Picea abies*.

Pre-1652 fires

The fire history before 1652 is more difficult to reconstruct spatially, because of the small number of records from that period. The oldest dated fire, in 1555, was dated in two *Pinus* stumps in the northern part of the reserve. Just south of these two stumps another *Pinus* (now also a stump), had regenerated shortly afterwards. In the eastern part of the reserve, fire scars were dated to 1603 and 1623. The 1603 fire had initiated the establishment of three other *Pinus* trees, now stumps. The 1623 fire seems to have been very local since no disturbances in ring patterns were found in neighbouring samples. In addition to these dates, we found two heavily decayed and charred *Pinus* stump remnants with four and five consecutive scars from fires that had occurred at 20-40 year intervals. They could not be dated, probably because they pre-dated the other samples. Presumably, these fires occurred at some time between the 15th and 17th centuries.

Charcoal fragments were present in eight of ten locations where it was searched for, giving additional evidence for fire presence. The two locations without charcoal were not different in site type compared to the other eight.

Logging history and past regeneration periods

The oldest living individuals of *Fagus* near the pollen site established between 1720 and 1750. According to the pollen diagram (Fig. 2), *Fagus* pollen values increased sharply ca. 1800, which most likely reflects the age (40 - 60 yr) when trees growing in a rather sparse forest enter the flowering stage (Drakenberg 1991). The oldest *Picea* generation seems to have a similar development with regeneration of trees starting in the 1750s. Extensive logging of *Pinus* took place in the reserve around the turn of the 18th/19th centuries, as shown by the many sampled *Pinus* stumps with youngest rings formed in the last decades of the 18th century, coincident with and after the presumed *Quercus* logging. In one case it was possible to date the logging of a *Pinus* with a one-year precision: it was cut late in 1812 or 1813. The logging of *Pinus* and *Quercus* in the late 18th and early 19th centuries coincides with the increase in *Fagus* and *Picea* pollen percentages (Fig. 3). Also, more recent logging has been conducted outside the core area several times during the 19th century. The core area seems unaffected by tree felling, except from a probable low-intensity logging operation ca. 1880-1890 that initiated a new generation of *Picea* and *Fagus*, the latter now suppressed. This presumed cutting could not be dated to the exact year since we found only rotten, but apparently cut, *Picea* stumps. No clear evidence for logging after this event has been found in the core area. The presumed logging of ca. 1880 fits well with the age of the current even-aged *Picea* stands south of the core area, which regenerated around 1885, probably after clear-cutting and sowing. North of the core area, the forest is dominated by fast growing *Picea* that became established somewhat later, in the 1920s. The cored trees from this area showed synchronous and rapid initial growth, similar to those south of the core area (data not shown).

Betula and *Alnus* are the only significant tree species in the pollen record (Björkman & Bradshaw 1996) (ca. 30 % respectively 20 %), not included in the tree-ring investigation. However, a few *Alnus* stumps (clumps with multiple-stems) together with dead remains of more *Alnus* stumps were found in the reserve in a drained, formerly wet area where *Picea* trees established in the beginning of the 20th century (Niklasson pers. obs.). Interestingly, almost no Alnus pollen was found in the top 15 cm of the profile (approximately equivalent to the last 100 yr), so it is likely that the decline in *Alnus* pollen matches well in time the observed *Alnus* cuttings, peat drainage and *Picea* establishment. *Betula* wood decays in a few decades and is therefore unsuitable for dendrochronological reconstructions. Both *Betula* and *Alnus* pollen are known to be greatly over-represented in pollen records.

Discussion

As deduced from the dated *Pinus* stumps and the single *Quercus* stump the rapid changes in forest composition should have been catalysed by humans. Knowing the logging and fire history, we think that climate is less likely to explain these patterns, even if climate is often put forward as the driving factor for changes in forest composition (Cheddadi et al. 1997; Huntley & Prentice 1993). The tree-ring data both improve and support the interpretation based on pollen analysis alone (Björkman & Bradshaw 1996).

The finding of a *Quercus* stump was surprising when considering its total absence in the reserve at present. In the region, old *Quercus* individuals are almost absent except in former 'inägor' (in-fields), along roads or in parks. However, according to historical documents, they were common in the 'utmark' (outland) in the past. The oak stump is situated on out-land at least 300 m from the nearest in-field with *Quercus* in the area. Eliasson & Nilsson (1999) claim that both logging and intense grazing by domestic animals were responsible for the disappearance of *Quercus* in southern Sweden, partly supported by other pollen analyses (Björkman 1996; Lindbladh et al. 2000). While the grazing issue may be discussed (Vera 2000), the logging should be indisputable. For the period when the dated

Quercus was alive, *Quercus* pollen represented 10-25% (Fig. 3) in the sediment. This abundance of pollen could not have been produced by this tree alone since it was located more than 100 m from the pollen site. Consequently, *Quercus* must have been a common tree species in the whole area up to the late 18th century. It is also interesting to note that *Quercus* was common in Siggaboda during a period with frequent fires. Only 15 m away from the oak stump, fires in 1741 and 1747 scarred a *Pinus* that was logged later (Fig. 3). Both the *Quercus* individual and the *Quercus* population (according to pollen analysis) appear to have been unaffected by these, and earlier, fires. Therefore it cannot be ruled out that *Quercus robur/petraea,* as a species, may be adapted to fire as are many North American *Quercus* species in similar vegetation regions (Abrams 1992; Smith & Sutherland Kennedy 1999).

Abundance of *Pinus* pollen is usually difficult to interpret. *Pinus* pollen disperses well and is known to be greatly over-represented in pollen diagrams (Prentice et al. 1987; Björse & Bradshaw 1996; Lindbladh et al. 2000). As in this case, when *Pinus* is abundant in the region (Björse et al. 1998), pollen percentage values less than ca. 10% from stand-scale records are usually interpreted as an absence of the species in the immediate surroundings (Bradshaw & Browne 1987). In the 16th century *Pinus* pollen increased to 15-20% which Björkman & Bradshaw (1996) interpreted as a post-fire establishment of this species in the reserve. This is now corroborated by a fire dated to 1555 and the establishment of many *Pinus* trees thereafter. Even if logging is the main factor behind the recent decline of *Pinus*, the absence of fire in the reserve after 1752 has made it very difficult for this species to regenerate by natural means. On a larger scale, a continuation of both strong fire suppression and current active planting of *Picea* monocultures will probably make *Pinus* increasingly rare throughout the region.

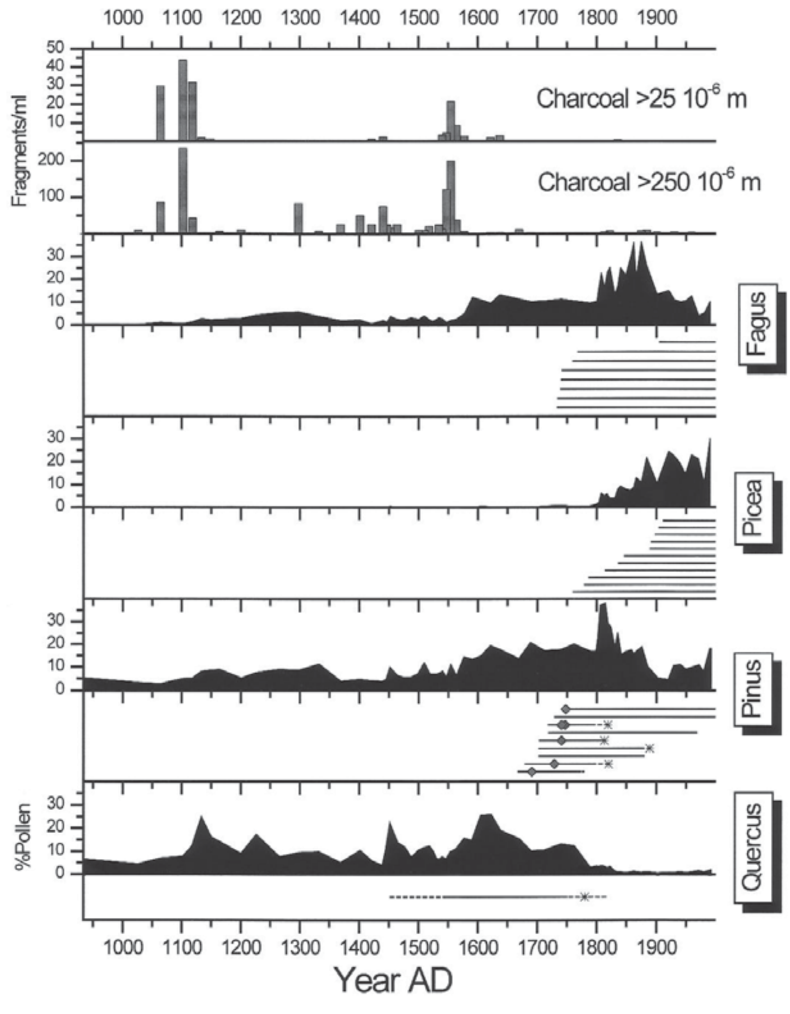

Fig. 3. Diagram showing charcoal fragments, pollen percentages and tree-ring analysed trees. Charcoal data show fragments > 25 µm and > 250 µm. Pollen percentages are shown for *Fagus*, *Picea*, *Pinus* and *Quercus* with all pollen types included in the pollen sum. Each horizontal line represents one tree from the 'age analysis area' (*Fagus sylvatica* and *Picea abies*) or from the core area (*Pinus sylvestris*) in the tree-ring scars. ✻ = represents date (or estimated date if on a dotted line) of cutting. Squares denotes cross dated fire year from fire scars.

Fires recorded in trees and peat deposits

The charcoal record seems to be a very conservative estimator of the actual fire regime, probably due to large differences in fire severity and intensity leading to large variations in charcoal formation and dispersal. Most tree-ring dated fires do not seem to have left any charcoal trace. Only one fire, scar-dated to 1555, fits in time with a peak in the sediment charcoal dated to ca. 1550 (Fig. 3). These results calls for caution when interpreting charcoal data in peat sediments, as it appears easy to overlook mild fires, at least in peat sediments (see Abrams & Seischab 1997; Ohlson & Tryterud 2000) Another important reason for the discrepancy could be the low time-resolution (usually on a scale of decades per sample) in accumulated peat compared to the annual resolution of tree rings. Sediments from laminated lakes seem to record mild fires better (Pitkänen et al. 1999). Nevertheless, charcoal fragments from deeper layers of peat are strong evidence that fires were also present before 1555.

We believe that humans started most of the fires dated by fire scars and that these fires were of relatively low intensity and severity. The small extent and patchiness of most fires, their uneven distribution over time and the sudden lack of fires after the 1750s, all point towards active and deliberate anthropogenic use of fire. A similar, sudden ending of fires in 1770 was reported from Norra Kvill national park (150 km to the northeast) (Niklasson & Drakenberg 2001). Furthermore, the fire frequency and the number of fires per area are manifold higher than the natural Lightning Ignition Density (LID) for the region (Granström 1993). An approximate comparison of the number of fires (11 fires over 50 ha and 193 years) in the reserve with the LID values for the region (12 - 15 fires over 10 000 ha and 100 yr) shows that the number of recorded fires exceeds the natural LID value by a factor of 70-100. The only reasonable explanation for this large discrepancy is the ignition of fires by humans. Humans probably burned the forest to improve grazing, as has been described from the boreal region (Niklasson & Granström 2000; Eriksson 2002). This was probably the case in the core area in particular, as the large boulders must have prevented the otherwise common use of slash and burn cultivation of turnips and cereals. The lack of cereal pollen in the sediment further confirms the absence of cultivation in the core area (Björkman & Bradshaw 1996).

Altogether, the fire record over the last 1000 years demonstrates a variable fire regime, probably following the human history of the area. The former Danish/ Swedish borderland was not colonized until the early middle ages. At this time fires seem to have been few but severe and/or intense. Later on, fires became more frequent and less severe and eventually ceased ca. 250 years ago, approximately at the time when the human population peaked in the area (Larsson 1975; Hyenstrand 1979; Lindbladh & Bradshaw 1998). Human use of fire (at least for times covered by the fire-scar record) has been much more common, more varied and more sophisticated than suggestions from historical documents and tradition. Fire must have been used for improving grazing, not only for slash and burn crop cultivation as is the common explanation. It takes a lot of experience and knowledge to control fire and burn just small patches. Except for native Americans in northeastern North America (e.g. Russell 1983) this kind of knowledge has rarely been documented for hemiboreal conditions. With the tree-ring supported data from Siggaboda we get a first insight into this previously unknown land-use practice in this part of Europe.

It is difficult to describe a natural fire regime for the area. However, the 1652 fire may have had natural causes as it covered a large area and was synchronous with many other fires in Sweden that summer (Kohh 1975; Niklasson & Granström 2000). Historical records also confirm that more fires occurred near our study area that year (Larsson 1989).

While early cuttings and ending of fires affected both *Quercus* and *Pinus* negatively, *Picea* and *Fagus* were promoted instead. During the period of tree-ring dated fires and earlier, *Fagus* was a minor component of the forest according to the pollen data. *Fagus* may have survived fires in the boulder-rich core area, as shown by the survival of young saplings and trees during fires dated in nearby pine stumps. The huge boulders may have acted as barriers by creating large fuel free patches that broke up and deprived fires of fuel. *Fagus* trees seldomly survive mild fires (Berli 1996). When they do, establishment seems to be strongly promoted by the fire and burnt ground (Karlsson 1996). When fires ceased (after 1748) *Fagus* and *Picea* were able to expand quickly from fire refuges to the surroundings where fires had earlier been lethal. A similar development where *Picea* was strongly promoted after fire suppression was described by Bradshaw & Hannon (1992) from the Fiby forest in Sweden, another hemiboreal forest, but north of *Fagus*' distribution during the Holocene.

Whatever the causes are, neither *Quercus* nor *Pinus* regenerate in the forest any longer, even if seed sources are available at rather short distances. We do not know when grazing ceased in the forest but fires evidently ceased 250 years ago and either, or both in combination, were probably important for the earlier oak dominated forest as often hypothesized in the recent paleoecological literature (Mason 2000; Vera 2000; Nilsson et al. 2001; Svenning 2002).

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