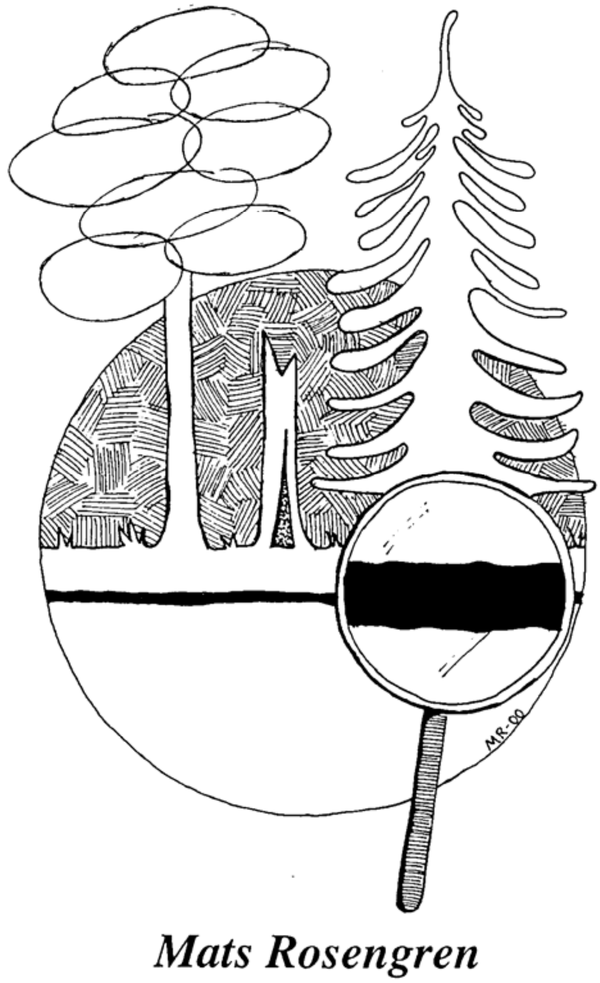
Institutionen för skoglig vegetationsekologi
SLU
901 83 UMEÅ

Is it possible to detect fire history by dating charcoal in humus? A case study from 3 stands in boreal Sweden.



Mats Rosengren

Examensarbete i biologi, 20p.
Handledare: Greger Hörnberg
November 2000

FÖRORD

Denna studie utfördes som ett examensarbete omfattande 20 poäng vid Institutionen för skoglig vegetationsekologi, Skogsvetenskapliga fakulteten, Sveriges Lantbruksuniversitet (SLU) i Umeå. Examensarbetet är en obligatorisk del av min programutbildning till skoglig magister med biologisk inriktning.

Först och främst skulle jag vilja tacka min handledare Greger Hörnberg för verkligt engagerad och inspirerande vägledning. Jag skulle även vilja tacka Olle Zackrisson för initierandet av denna studie, samt Ulf Segerström och Tom DeLuca för värdefulla kommentarer till manuskriptet. Tack även till Länsstyrelsen i Norrbotten för arbetstillståndet i Suorke naturreservat.

Umeå den 15 november 2000

Mats Rosengren

CONTENTS

Is it possible to detect fire history by dating charcoal in humus? A case study from 3 stands in boreal Sweden.

Abstract

This study estimates the total amount of charcoal/ha and examines the possibility of detecting fire history by radiocarbon dating charcoal in humus from three stands in northern Sweden; one *Pinus-Cladina*, one *Pinus-Vaccinium* and one *Picea*-herb stand. All stands have the same fire history documented by dendrochronology. Samples of brushwood charcoal were taken in the uppermost and lowermost part of the charcoal layers, and radiocarbon dated with Accelerator Mass Specthrometry (AMS). The results show that the *Pinus-Vaccinium* stand has the largest charcoal record, c. 5400 kg/ha, and the *Pinus-Cladina* stand the smallest, c. 850 kg/ha. The charcoal samples are too young (≤ 600 years) to give accurate dating results for a comparison with the documented fires dated by dendrochronology. It is concluded that the persistence of charcoal in humus is low and that wildfire is the most likely agent of charcoal degradation. Further, it is suggested that the two *Pinus* stands, having the youngest charcoal, are characterized by severe fires consuming old charcoal, while the fires in the *Picea*-herb stand generally are less severe, making it possible for old charcoal to accumulate. Therefore, the possibility of detecting fire history by radiocarbon dating charcoal in humus is probably restricted to stands where fire severity is lower or similar to the *Picea*-herb stand.

Är det möjligt att bestämma brandhistorik genom datering av träkol i humus? En studie av 3 bestånd i boreala Sverige.

Sammanfattning

I denna studie uppskattas den totala mängden träkol/ha i tre bestånd i norra Sverige. Tillika undersöks möjligheten att bestämma brandhistoriken genom ^{14}C-datering av träkol i humus. I alla tre bestånden; ett *Pinus-Cladina*-, ett *Pinus-Vaccinium*- och ett *Picea*-ört-bestånd, är brandhistoriken, dokumenterad med dendrokronologi, densamma. Träkol från risvegetation extraherades ur de översta och understa delarna av kollagren och daterades med Accelerator Mass Specthrometry (AMS). Resultaten visar att den största kolmängden, ca 5400 kg/ha, återfinns i *Pinus-Vaccinium*-beståndet, medan i *Pinus-Cladina*-beståndet finns den minsta mängden, ca 850 kg/ha. Det extraherade träkolet är alltför ungt (≤600 år) för att ge tillräckligt säkra dateringar för att en jämförelse med den dokumenterade brandhistoriken skall vara möjlig. Det konstateras att träkol i humus ej är beständigt, och att brand är den mest troliga nedbrytande faktorn. Det konstateras vidare att de två *Pinus*-bestånden, som innehåller det yngsta kolet, karaktäriseras av hårda bränder som bryter ned gammalt träkol, medan bränderna i *Picea*-ört-beståndet i regel är mindre hårda, vilket möjliggör en ackumulering av träkol. Följaktligen är möjligheten att bestämma brandhistorik genom ^{14}C-datering av träkol i humus förmodligen begränsad till bestånd där brandhårdheten är liknande, eller svagare än, i *Picea*-ört-beståndet.

Introduction

Wildfire is a natural disturbance of great importance in the boreal forest of Scandinavia (Zackrisson 1977) as it alters vegetation composition (Wardle et al. 1998) and affects ecological processes like the cycling of nutrients (Kimmins 1997). The produced charcoal adsorbes allelophatic substances (Zackrisson et al. 1996) which may result in enhanced biological activity and vegetation growth in the ecosystem (Wardle et al. 1998). Also, a large number of plants and animals are dependent on burnt areas (Esseen et al. 1997, Kimmins 1997, Muona and Rautanen 1994). In order to understand the characteristics and function of the present boreal forest, knowledge of its past, including fire dynamics, is required. This is essential for conservation aspects as well as for the commercial forestry striving to mimic natural forest disturbance in their management.

During the last century, different methods for revealing fire history have been developed (Patterson et al. 1987). In dendrochronology wood cores from old trees are taken and the fire scars are dated by counting the year rings (Niklasson et al. 1998, Zackrisson 1977). Using pointer-years and cross-dating both living and dead trees can be used, the dating is very accurate and the fire scars indicate severe local fires (Niklasson 1998). However, it is difficult to detect fires older than one millennium, as well as to find old fire scarred trees in areas used for commercial forestry. There is also a risk of not discovering spatially small fires (Niklasson and Granström 2000).

Quantifying microscopic fossil charcoal, by counting number or measuring surface area of particles in cores taken from lacustrine sediments (Larsen and MacDonald 1998 (a), (b), Maenza-Gmelch 1997, Mensing et al. 1999, Turcq et al. 1998, Whitlock and Millspaugh 1996) or peat (Bradshaw and Hannon 1992, Meen 1998, Segerström et al. 1996, Smedstad 1997) are also frequently used methods. The approach makes it possible to identify fire patterns several thousand years back in time (Clark 1997, Long et al. 1998), but it is difficult to determine if the fires are local or regional (Long et al. 1998), and there is a risk of not covering all historical wildfires when examining segments extracted uncontiguously from the sediment core (Clark 1988, Patterson et al. 1987). Also, the characteristics of deposition and redeposition may sometimes cause confusion when interpreting data (Patterson et al. 1987).

Fire data can also be obtained by investigating fossil charcoal records in forest humus (Carcaillet et al. 1997, Horn and Sanford 1992, Ogden et al. 1998, Ohlson and Tryterud 1999, Zackrisson 1977). Because macroscopic charcoal is seldom transported any greater distances from where it is produced (Clark 1988, Ohlson and Tryterud 2000, Patterson et al. 1987, Whitlock and Millspaugh 1996), occurrence indicates local fires (Ohlson and Tryterud 1999, 2000). However, the risk of fragmentation of charred particles by e.g. soil fauna and root activity is not negligible (Carcaillet et al. 1997). Often, the charcoal record is found in a single layer, on top of the mineral soil, which makes it difficult to quantify the number of fires and to identify single fire events. However, if frequent fires do not totally consume the humus, charcoal would deposit in a sequence making it possible to date individual fire events by the use of radiocarbon dating by Accelerator Mass Specthrometry (AMS), although the method can show a great uncertainty if the charcoal is younger than 200 years (Bowman 1990). At present, there is a lack of data indicating if it is possible to detect individual fires in a highly precise scale from a single charcoal layer in humus.

This paper deals with the fossil charcoal record between humus and mineral soil in three different forest types in the boreal zone of Sweden. The purpose of this study was to

differentiate age of charcoal by depth where the oldest is found at the bottom.
The specific aims were;
- to estimate the total amount of charcoal (kg/ha),
- to examine the possibility of detecting fire history, by dating charcoal from brushwood at different depths in humus/soils, to maximize temporal and spatial resolution.

Humus/soil samples were taken from three different stand types with documented fire history established by dendrochronology, their charcoal content was divided into vertically contiguous segments, and the charcoal was weighed. Finally AMS was performed to date the brushwood charcoal at top and bottom of the same charcoal layer.

The results indicate if it is possible to detect fire history by dating selected parts of a single charcoal layer. Further, the results contribute to the knowledge of amount, production and persistence of charcoal in the boreal forest.

Methods

Study site
The study area, Suorke, is situated in the boreal forest, 230-240 m.a.s.l., 65 km south of Jokkmokk, Norrbotten county, Sweden (66° 01′ N, 19° 51′ E) (Figure 1). The climate is continental, with a mean temperature in January and July of –13 °C and +15 °C respectively. The length of growing season (number of days with a mean temperature >5 °C) is approximately 135 days and annual precipitation is 600 mm, of which 40 % is snow covering the ground 175-200 days/year (Anon. 1995). Soils are predominantly podzols composed of coarse to medium sand.

Description of the stands

In the Suorke area three different stands were studied, namely a *Pinus-Cladina* stand, a *Pinus-Vaccinium* stand and *Picea*-herb stand (Figure 1). The fieldwork took place at two occasions during the summer of 1999. The stand data and humus/soil sampling procedure was done in 7 – 11 June with an additional inventory of the vegetation in 4 – 6 August. Stand data was collected on 3 circular plots (radius of 10 m) in each stand (Table 1), and for a complete list of species, see Appendix. The documented fire history of the stands by dendrochronology (Zackrisson unpublished) can be seen in Table 1.

The *Pinus-Cladina* stand is an open *Pinus sylvestris* forest, mixed with a few *Betula pubescens*, on flat, nutrient-poor ground. Most trees form clusters around the largest specimens. Fire-scars are visible on larger trees and snags. *Cladina rangiferina, Cladina arbuscula*, and *Cetraria islandica* are characterizing the ground layer, except under the clusters of trees, where *Pleurozium schreberi* and *Dicranum sp.* are dominant. The field layer is characterized by *Calluna vulgaris* and *Vaccinium vitis-idaea* together with *Empetrum nigrum, Vaccinium myrtillus* and *Arctostaphylos uva-ursi*. The average humus and fermentation layer thickness is 3 (± 0.3) cm.

The *Pinus-Vaccinium* stand is a more productive, single layered *Pinus sylvestris* forest with a few *Betula pubescens* and *Picea abies*. Several fire-scars are visible on the standing trees. A few nearly decomposed logs are present. The ground layer is characterized by lichens and

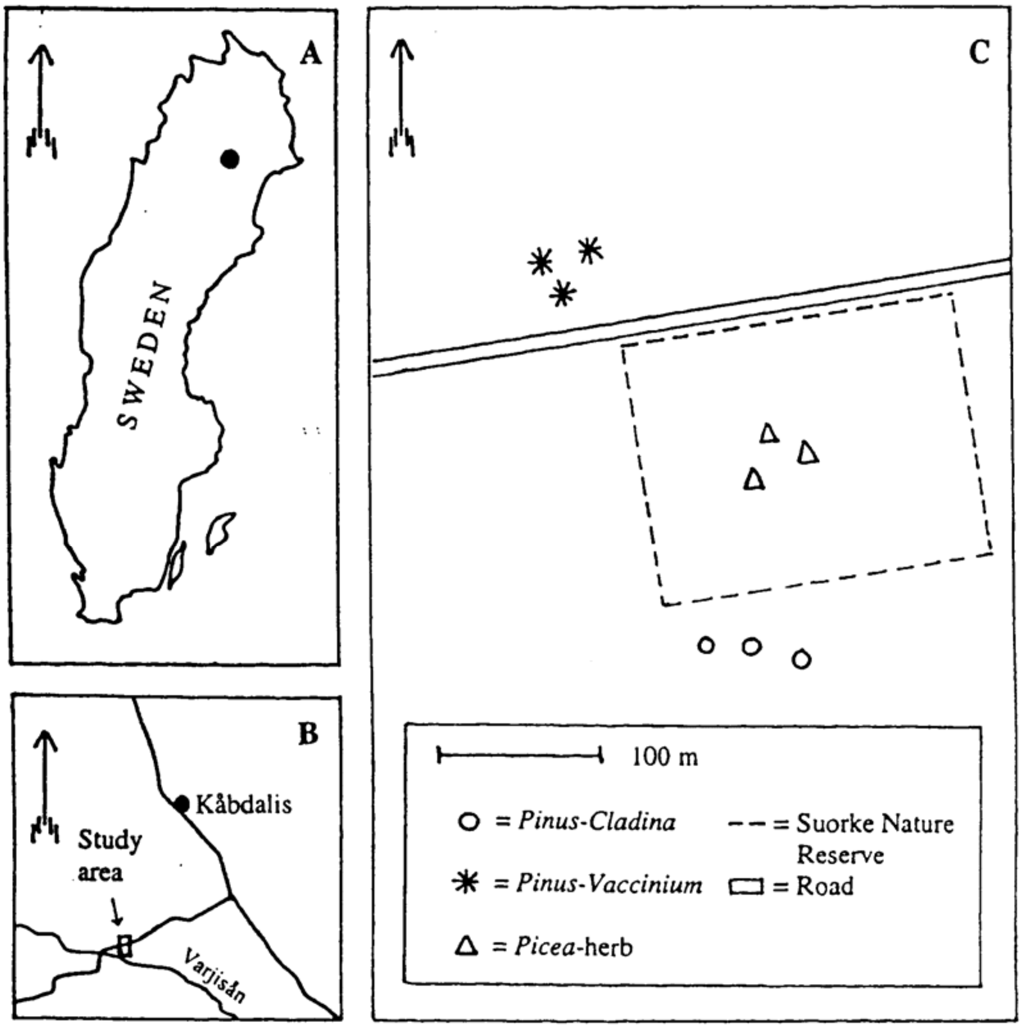


Figure 1. The study area is located in northern Sweden (A), along the road between the Varjisån river and the Kåbdalis village (B). The study area with the 9 sample plots is pictured in (C).

mosses such as *Cladina rangiferina, Cladina arbuscula, Hylocomium splendens* and *Polytrichum commune*. The field layer is characterized by *Vaccinium vitis-idaea* and *Vaccinium myrtillus* which, together with *Calluna vulgaris, Empetrum nigrum,* and *Vaccinium uliginosum* form a denser mat than in the *Pinus-Cladina* stand. Other characteristic species are *Deschampsia flexuosa, Ledum palustre* and, in the hollows *Rubus chamaemorus* and *Equisetum sylvaticum*. The average humus and fermentation layer thickness is 6.5 (± 0.7) cm.

The *Picea*-herb stand is located in the Suorke nature reserve. *Picea abies* dominates the tree layer, some specimens of *Pinus sylvestris*, *Betula pubescens* and *Populus tremula* of large dimensions being present. This stand differs from its surroundings in having high productivity mainly due to subsurface waterflow. The ground layer, on this slightly sloping ground, is characterized *by Hylocomium splendens, Polytrichum commune* and *Pleurozium schreberi*. Field layer vegetation is more diverse consisting of 30 species including *Geranium sylvaticum, Actaea erythrocarpa, Galium triflorum, Roegneria canina, Paris quadrifolia, Ribes spicatum, Calypso bulbosa* and *Matteuccia struthiopteris*. The cover of brushwood species is low. The stand has a few fire-scars, and the average humus and fermentation layer thickness is 9.5 (± 0.7) cm.

Stand	Tree species composition (%)	Average age (± SE)	Basal area (m^2)	Standing volume (m^3)	Production of wood biomass (m^3/ha/yr)	Number of fire scars/sample plot
Pinus-Cladina	98/0/2	152 (± 27)	12	120	2	3/4/6
Pinus-Vaccinium	94/3/3	173 (± 7)	20	160	4.3	3/5/6
Picea-herb	8/77/15	142 (± 11)	37	449	7.1	0/0/0
Documented fire years: 1441, 1652, 1697, 1758 and 1831						

Table 1. Stand data and documented fire history. Tree species composition is presented as percent of total basal area, for *Pinus sylvestris*/*Picea abies*/deciduous tree species. The annual production of wood biomass is estimated according to Hägglund and Lundmark (1981). The fire history, identical for all stands, is documented by dendrochronology (Zackrisson unpublished).

Locating the sample plots and sampling

In each stand a research area of 75 x 50 m (3750 m^2) was randomly established and marked. Plots with the thickest humus layer, i.e. hollows and mossdominated parts, were searched through with particular intensity in order to find as much charcoal as possible, which would probably enlarge the span in charcoal age. After a minimum of 200 trials, three plots were chosen. All three sample plots in the *Pinus-Cladina* stand and two out of three plots in the *Pinus-Vaccinium* stand were situated where the ground layer vegetation was dominated by mosses. In the *Picea*-herb stand no such trend was obvious.

At each plot a cubical humus/soil sample was taken using a spade, and measurements of the sample size was made. Due to ground characteristics, there was a variation in size (cm); length 13-16; width 13-18; and depth 9-14 (all soil samples included at least 1.5 cm of mineral soil). One front of the profile was measured in more detail regarding thickness of humus, charcoal layer (when visible) and mineral soil. The top and bottom of the charcoal layer was marked with pins. A sketch was made visualising this front surface. Each soil sample was folded in plastic sheeting, aluminium foil and finally in a plastic bag before taken to the freezer (-18 °C), in which they were placed 6-12 hours later. In handling the samples, direct contact with hands was restricted to a minimum. The thickness of the humus layer was also measured at five spots, with an interval of 2 m, direction westward from each sample plot.

Total amount of charcoal

At the laboratory the total amount of charcoal was defined, as well as the fraction of charcoal derived from wood and brushwood at different humus depths. Using a scalpel, rectangular segments were cut vertically from the top, down along the described soil sample front, and placed in petri dishes (Figure 2). All sampling was done when the humus/soil sample was in a half thawed state, to maximize cutting precision, and each cut was measured with a ruler. Before the next segment was cut, all tools were cleaned to avoid contamination. For each segment, the front surface of the sample was cut clean at least 0.3 cm, to eliminate the risk of contamination from the spade used in field. This procedure resulted in the following sample sizes (cm); width 2, depth 0.5 and length 2, giving a volume of 2 cm^3. The depth of 0.5 cm was found to be the thinnest possible layer to cut out accurately using a scalpel. From the petri dish the segment was transferred with a spatula to a new dish, where it was stirred in water.

Samples were taken from the surface down to >0.5 cm into the mineral soil. Each dish was examined for charcoal, using a stereomicroscope (Wild Heerbrugg M3, magnification 6.4x and 16x). Charcoal particles (≥0.5 mm) were transferred to a new petri dish containing water, where identification and separation of charcoal originating from brushwood was made. The identified particles were put into tubes (Labora 1.75 ml), dried in 70 °C for 12 hours, and weighed, (Mettler AT460, 0.0 mg). This process was completed for each soil sample before dealing with the next. After processing one soil sample from each stand it became obvious that the charcoal was concentrated in one vertically distinct layer, between the humus layer and the mineral soil. The weights were transformed to kg/ha values.

Dating charcoal from brushwood at different depths

Radiocarbon dating was used for macroscopic charcoal ($\geq$0.5 mm) because the size indicates local fire (Ohlson and Tryterud 1999, 2000). Focus was on charcoal originating from brushwood, i.e. species of e.g. *Vaccinium* and *Empetrum*, instead of from wood, i.e. trees, because the shorter life-span of brushwood minimizes the "old-wood effect" when dated with AMS (Bowman 1990, Carcaillet 1998, Horn and Sanford 1992, Ogden et al. 1998).

To examine the possibility of detecting fire history by radiocarbon dating charcoal from brushwood at different depths, the same procedure of segment extraction and handling as for the estimation of total amount and fraction was used, with the following modifications.

At least 4.0 mg (dry weight) of pure charcoal is recommended to get an accurate radiocarbon dating with AMS (M. Söderman, personal comment). When collecting that amount of charcoal, the aim was to utilize the smallest horizontal area of the soil samples as possible thus minimizing the risk of sample errors due to the assumed irregular vertical shape of the charcoal layer. Therefore, the soil sample from each stand, which contained the largest amount of charcoal originating from brushwood in the uppermost and lowermost cm of the charcoal layer, was chosen. From those, sample segments were cut, with (cm); length 4, width 4 and depth 0.5, giving a volume of 8 cm^3. The gradient of segment sampling was placed where it was found most suitable considering the characteristics of each soil sample.

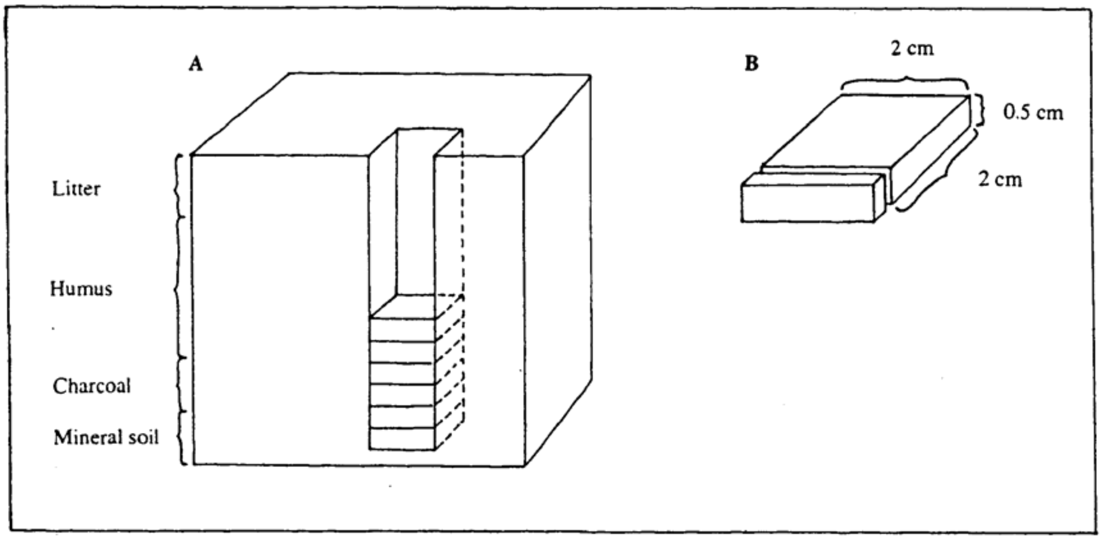


Figure 2. Rectangular segments were cut in a vertical gradient downward from the top, along the described soil sample front (A). For each segment, the front surface of the sample was cut clean at least 0.3 cm. This procedure resulted in the following sample sizes (cm); width 2, depth 0.5 and length 2, giving a volume of 2 cm^3 (B).

Examination began with the segments from the very top and bottom. If a segment did not contain any or if it contained extremely small amounts of charcoal, the sample was discarded and examination of the next level, closer to the vertical centre of the charcoal layer began. This process continued until a segment, that alone should fulfil the requirement, was encountered. One crucial condition was, that at least one segment was left unexamined, giving a horizon of ≥0.5 cm between the selected charred brushwood pieces from the lower and upper layer. When finished, the *Pinus-Cladina* stand had one segment (0.5 cm) left, the *Pinus-Vaccinium* stand four (2.0 cm) and the *Picea*-herb stand two (1.0 cm).

Two segment samples from each stand, in all six samples of 8 cm^3 each, were chosen initially. At this stage, the demand for ≥4.0 mg was fulfilled for two out of these six. For the remaining additional sampling was necessary. For the upper segment of the *Pinus-Cladina* soil sample as much as 12.5 cm^3 in addition were needed before reaching ≥4.0 mg. The additional samples were cut as the previous, by horisontally enlarging the already sampled area. Six samples, each including more than 4.0 mg of charcoal originated from brushwood, were sent for dating at the Ångström Laboratory in Uppsala. The radiocarbon dates were calibrated according to Stuiver and Reimer (1993).

Results

Total amount of charcoal

The smallest mean amount of charcoal (kg/ha) was found in the *Pinus-Cladina* stand and the largest was found in the *Pinus-Vaccinium* stand (Table 2). All soil samples, except *Picea*-herb 2, indicate that charcoal from wood was the dominant type of charcoal in the stands. In the *Pinus-Vaccinium* stand the largest mean amount (kg/ha) of, but the lowest proportion of charcoal from brushwood, was found. Charcoal from brushwood, had the highest proportion in the upper half of the charcoal layer, in five of the humus/soil samples. Thus, four samples had the highest proportion in the lower half. The average thickness of the charcoal layer was smallest in the *Picea*-herb stand and largest in the *Pinus-Vaccinium* stand (Table 2).

Sample	Amount of charcoal (kg/ha)				Average charcoal layer thickness (±SE) (cm)	Proportion of brushwood in each sample (%)	
	Brushwood	Wood	Total	Average (± SE)		Upper half	Lower half
Pinus-Cladina 1	103	1728	1831			6	5
Pinus-Cladina 2	23	95	118	843 (± 511)	2.8 (± 0.4)	5	29
Pinus-Cladina 3	270	310	580			49	45
Pinus-Vaccinium 1	383	8360	8743			2	7
Pinus-Vaccinium 2	443	5540	5983	5373 (± 2144)	4.3 (± 0.7)	5	12
Pinus-Vaccinium 3	250	1143	1393			59	5
Picea-herb 1	48	2805	2853			0	10
Picea-herb 2	280	135	415	1251 (± 801)	2.5 (± 0.3)	72	54
Picea-herb 3	63	423	486			23	5

Table 2. The amount of charcoal (kg/ha) for each humus/soil sample, as well as the average for each stand. Further, the average charcoal layer thickness (cm) for each stand, and the proportion of charcoal (%) derived from brushwood in the upper and lower half respectively, of the charcoal layer in each sample.

Dating charcoal from brushwood at different depths

The ^{14}C dates for the charcoal segments vary in age between 110 ± 80 and 605 ± 85 years

(BP) (Table 3). Between the upper and lower segments of the *Pinus-Cladina* and the *Picea*-herb stands there is a possible difference in ^{14}C age. The very oldest charcoal is found in the *Picea*-herb stand. The calibrated dates, with minimum and maximum age ranges (AD), are separated for the segments from the *Picea*-herb stand only. For the *Pinus-Vaccinium* stand, neither the ^{14}C dates nor the calibrated dates show any difference in age between the segments (Table 3).

Sample	^{14}C age (BP)	Calibrated age (AD), intercept, min. and max. age ranges at 2σ	Sample code
Pinus-Cladina upper	110 ± 80	1650 (1710, 1820, 1830, 1880, 1910, 1950) 1955	Ua 15747
Pinus-Cladina lower	330 ± 80	1432 (1520, 1560, 1630) 1954	Ua 15748
Pinus-Vaccinium upper	235 ± 80	1474 (1660) 1955	Ua 15749
Pinus-Vaccinium lower	200 ± 65	1524 (1670, 1780, 1800, 1950) 1955	Ua 15750
Picea-herb upper	165 ± 80	1527(1680, 1750, 1810, 1940, 1950) 1955	Ua 15745
Picea-herb lower	605 ± 85	1275 (1320, 1340, 1390) 1448	Ua 15746

Table 3. The ^{14}C ages expressed as age BP, and the calibrated ages expressed as age AD for the charcoal samples. The analyses were made by the Ångström Laboratory, Uppsala. The calibrations were made with the calibration programme Calib 3.0 (Stuiver and Reimer 1993).

Discussion

Total amount of charcoal

The results show, that the largest soil charcoal record, approximately 5400 kg/ha, was found in the *Pinus-Vaccinium* stand and the smallest, approximately 850 kg/ha, was found in the *Pinus-Cladina* stand (Table 2). Zackrisson et al. (1996) estimated the mean value of charcoal/ha, in 12 *Pinus sylvestris* stands with *Empetrum-Vaccinium* dominance in Sweden, to 1460 kg/ha (in the range 984-2074 kg/ha). Clark et al. (1998) made an intensive experimental burn in a *Pinus sylvestris* forest in Siberia, which produced approximately 730 kg/ha of new charcoal, equivalent to 2 % of the fuel consumed. In a similar experimental burn in one *Pinus sylvestris* and two mixed *Pinus sylvestris*/*Picea abies* stands in Norway and Sweden, a mean of 235 kg/ha and maximum of 6800 kg/ha of new charcoal (≥0.5 mm) was produced (Ohlson and Tryterud 2000). Thus, with one exception that maximum value was higher than the maximum results in this study (Table 2). Further, the mean values in this study were higher than the result of Clark et al. (1998), but most of the mean and maximum values were below the corresponding results of Zackrisson et al. (1996). Thus, the results in this study seem reasonable when compared to the previous studies, although the methods were different.

Amount and production of charcoal in the stands

There are differences between the stands, regarding the total amount of charcoal/ha, which is due to the variation in charcoal derived from wood (Table 2), as well as of the proportion of charcoal derived from brushwood and wood. This may result from differences in intensity and severity of fire as well as amount and type of fuel (Clark et al. 1998, Ohlson and Tryterud 2000, Patterson et al. 1987).

In the *Pinus-Cladina* stand the smallest total amount (kg/ha) of charcoal was found (Table 2). The main reason for this is probably the low productivity that results in a small amount of potential fuel, resulting in ground fires of low intensity. This is also the reason for the relatively high proportion of charcoal from brushwood in this stand.

The largest total amount (kg/ha) of charcoal as well as the largest amount (kg/ha) of charcoal derived from brushwood, was found in the *Pinus-Vaccinium* stand (Table 2). The reason is probably that the *Pinus-Vaccinium* stand has been more affected by intensive fires than the *Picea*-herb stand, and produces more potential fuel (Schimmel 1993, Schimmel and Granström 1996) than the *Pinus-Cladina* stand. Also, if the field layer vegetation has been dominated by brushwood for some time, the actual amount of brushwood charcoal will be large although the proportion is small.

In the *Picea*-herb stand a total amount of approximately 1250 kg/ha of charcoal was estimated, thus less than in the *Pinus-Vaccinium* stand but more than in the *Pinus-Cladina* stand (Table 2). Since the charcoal present has been produced during a longer time period than in the other stands, this indicates that fires have been less intensive. Although the *Picea*-herb stand produces the most potential fuel, due to high fertility, the total amount of charcoal is relatively small but with quite a high proportion of charcoal derived from brushwood. There is a dominance of charcoal from brushwood in *Picea*-herb soil sample 2, although brushwood vegetation at present is sparse. This confirms that vegetation types are not static (Huntley 1988), thus charcoal type in humus can not be predicted by looking at present vegetation.

There seems to be no relationship between the total amount of charcoal and the thickness of the charcoal layer. However, 3 samples per stand are insufficient to give a reliable evidence of this.

Dating charcoal from brushwood at different depths

The ^{14}C dates as well as the calibrated dates for the charcoal segments from the *Picea*-herb stand are separated indicating that the charcoal probably was produced in different fires (Table 3). The oldest charcoal is found in the lower segment and may even origin from a fire older than the oldest documented fire in 1441 (Table 1). The young age of charcoal from all the other segments makes a comparison with the fire history documented by dendrochronology impossible.

Persistence and degradation of charcoal

Zackrisson et al. (1996) found no correlation between time since last fire and amount of charcoal in the soil. They concluded that charcoal is very persistent and that no contradictory data existed. However, Ohlson and Tryterud (2000) made an approximate calculation and stated that if charcoal is completely persistant, the mean fossil charcoal record in a fire-prone boreal forest stand would be 23500 kg/ha. They concluded that charcoal is not very persistent, and found it likely that each fire consumes a proportion of the old charcoal. The oldest charcoal in this study, located in the *Picea*-herb stand, is approximately 600 years old, which indicates that charcoal is not very persistent against degradation. The oldest charcoal in the *Pinus* stands is even younger, which indicates that the rate of degradation is faster in those stands than in the *Picea*-herb stand. There are several potential factors that could be responsible for the degradation of charcoal in humus.

Indicative of the importance of wildfire is the fact that all the charcoal is located in one layer. This indicates that in at least some fires, the severity has been high enough for complete consumption of the humus layer. Consequently, at these occassions there could be a possible degradation of the old charcoal already present in the humus. This is the most likely reason for the lack of old charcoal in the sampled stands. It seems possible that the complete charcoal record present in the *Pinus-Vaccinium* stand was produced at the most recent fire, and that all the old charcoal was simultaneously degraded (Table 3). The oldest charcoal was found in the *Picea*-herb stand, which indicates that these fires have been less devastating to the charcoal record, i.e. less severe, than in the *Pinus* stands, which should result in a lower rate of charcoal consumption. In less severe fires, the charcoal closest to the humus, seemingly the youngest charcoal, should suffer a higher risk of being degraded. Consequently, in such a case the oldest charcoal could remain intact. On the other hand, it is possible that the older charcoal would be more sensitive to degradation, for some reason, in which case it would suffer the highest risk. However, at present no such studies have been made. There are other potential factors for charcoal degradation with a biological, physical, chemical or mechanical character, such as activity of soil organisms or weathering (Atkinson 1957, Rolfsen 1980). However, no conclusions concerning these factors could be made from the results in this study.

The possibility of detecting fire history

In evaluating the usefulness of the method for possible detection of fire history with high temporal and spatial resolution used in this study, it is important to stress that even charcoal samples of 330 years (^{14}C age) is considered young. This strongly reduces the temporal precision of the presented data, a fact that was stressed when the calibrated datings resulted in wide timespans, 522 years at the most (Table 3).

The *Pinus* stands have probably been exposed to more severe fires consuming the old charcoal, thus the simultaneously produced charcoal record is young. Therefore, it seems that dating performed in this way is not recommendable for detecting the fire history in stands similar to the *Pinus* stands in this study. However, in stands similar to the *Picea*-herb, where accumulation of charcoal seems possible to a greater extent due to less severe fires, the circumstances may be more beneficial regarding dating. To avoid the "old-wood effect" the presence of brushwood charcoal in the bottom of the charcoal layer is a prerequisite for being able to detect the oldest fire, with high temporal precision, using radiocarbon dating. In this study, the contents of charcoal derived from brushwood seem to be evenly distributed throughout the charcoal profiles. Even in the *Picea*-herb stand, there is enough older brushwood charcoal to conduct radiocarbon dating. For example, if such a stand is also characterized by long fire return intervals, theoretically each segment of charcoal sampled in a vertical gradient could be separated in time from the sample just above and below. This could make radiocarbon dating useful as a complement to dendrochronology. At least it would be possible to extend the time period studied and to detect the number of historic fires, still not the exact dates. However, for that purpose it might be worth to consider alternative methods, such as e.g. quantification of charcoal layers in peat deposits (Tryterud 2000), which is easier, cheaper and faster.

References

Anonymous 1995. Sveriges Nationalatlas – Klimat, sjöar och vattendrag. 1st edition. SNA.

Atkinson, R. J. 1957. Worms and weathering. Antiquity 31; 219-233.

Bowman, S. 1990. Radiocarbon dating - Interpreting the past. British Museum Publications Ltd. London. 64 pp.

Bradshaw, R. and Hannon, G. 1992. Climatic change, human influence and disturbance regime in the control of vegetation dynamics within Fiby Forest, Sweden. Journal of Ecology 80; 625-632.

Carcaillet, C. 1998. A spatially precise study of Holocene fire history, climate and human impact within the Maurienne valley, North French Alps. Journal of Ecology 86; 384-396.

Carcaillet, C., Barakat, H. N., Panaïotis, C. and Loisel, R. 1997. Fire and late-Holocene expansion of *Quercus ilex* and *Pinus pinaster* on Corsica. Journal of Vegetation Science 8; 85-94.

Clark, J. S. 1988. Particle motion and the theory of charcoal analysis: Source area, transport, deposition, and sampling. Quaternary Research 30; 67-80.

Clark, J. S. 1997. Facing short-term extrapolation with long-term evidence: Holocene fire in the north-eastern US forests. Journal of Ecology 85; 377-380.

Clark, J. S., Lynch, J., Stocks, B. J. and Goldammer, J. G. 1998. Relationships between charcoal particles in air and sediments in west-central Siberia. The Holocene 8 (1); 19-29.

Esseen, P.A., Ehnström, B., Ericson, L., and Sjöberg, K. 1997. Boreal forests. Ecological Bulletins 46; 16-47.

Horn, S. P. and Sanford, R. L. Jr. 1992. Holocene fires in Costa Rica. Biotropica 24 (3); 354-361.

Huntley, B. 1988. Europe. In: Huntley, B. and Webb III, T. (eds), Vegetation History. Handbook of vegetation science vol 7. Kluwer Academic Publishers. Dordrecht, pp 341-383.

Hägglund, B. and Lundmark, J. B. 1981. Bonitering, diagram och tabeller. Skogsstyrelsens förlag, Jönköping.

Kimmins, J. P. 1997. Forest ecology – A foundation for sustainable management. 2nd edition. Prentice-Hall (New Jersey), pp 296-313.

Larsen, C. P. S. and MacDonald, G. M. 1998 (a). An 840-year record of fire and vegetation in a boreal white spruce forest. Ecology 79 (1); 106-118.

Larsen, C. P. S. and MacDonald, G. M. 1998 (b). Fire and vegetation dynamics in a jack pine and black spruce forest reconstructed using fossil pollen and charcoal. Journal of Ecology 86; 815-828.

Long, C. J., Whitlock, C., Bartlein, P. J. and Millspaugh, S. H. 1998. A 9000-year fire history from the Oregon Coast Range, based on a high resolution charcoal study. Canadian Journal of Forest Research 28; 774-787.

Maenza-Gmelch, T. E. 1997. Late-glacial – early Holocene vegetation, climate, and fire at Sutherland Pond, Hudson Highlands, southeastern New York, U.S.A. Canadian Journal of Botany 75; 431 – 439.

Meen, E. 1998. Makroskopisk trekull i torv – en paleoøkologisk undersøkelse av romlig variasjon på regional og lokal skala. Candidate thesis, Department of Biology and Nature Conservation, Agricultural University of Norway. 72 pp.

Mensing, S. A., Michaelson, J. and Byrne, R. 1999. A 560-year record of Santa Ana fires reconstructed from charcoal deposited in the Santa Barbara Basin, California. Quaternary Research 3; 295-305.

Muona, J. and Rutanen, I. 1994. The short-term impact of fire on the beetle fauna in boreal coniferous forest. Annales Zoologici Fennici 31(1); 109-121.

Niklasson, M. 1998. Dendroecological studies in forest and fire history. Doctoral thesis, Swedish University of Agricultural Sciences. Acta Universitatis Agriculturae Sueciae, Silvestria 52.

Niklasson, M. and Granström, A. 2000. Numbers and sizes of fires: Long term spatially explicit fire history in a north-swedish boreal landscape. Ecology 81; 1484-1499.

Niklasson, M., Hörnberg, G. and Zackrisson, O. 1998. Age structure and disturbance history in a boreal Pinus-Picea forest, N. Sweden. Acta Universitatis Agriculturae Sueciae, Silvestria 52.

Ogden, J., Basher, L. and McGlone, M. 1998. Fire, forest regeneration and links with early human habitation: Evidence from New Zealand. Annals of Botany 81; 687-696.

Ohlson, M. and Tryterud, E. 1999. Long-term spruce forest continuity – a challenge for a sustainable Scandinavian forestry. Forest Ecology and Management 124; 27-34.

Ohlson, M. and Tryterud, E. 2000. Interpretation of the charcoal record in forest soils: forest fires an their production and deposition of macroscopic charcoal. The Holocene 10; 519-525.

Patterson, W. A., Edwards, K. J. and Maguire, D. J. 1987. Microscopic charcoal as a fossil indicator of fire. Quaternary Science Reviews 6; 3-23.

Rolfsen, P. 1980. Disturbance of archaeological layers by processes in the soil. Norwegian Archaeological Review 13 (2); 110-116.

Segerström, U., Hörnberg, G. and Bradshaw, R. 1996. The 9000-year history of vegetation development and disturbance patterns of a swamp-forest in Dalarna, northern Sweden. The Holocene 6, 1; 37-48.

Schimmel, J. 1993. Fire behaviour, fuel succession and vegetation response to fire in the Swedish boreal forest. Dissertation Swedish University of Agricultural Sciences, Umeå.

Schimmel, J. and Granström A. 1996. Fire severity and vegetation response in the boreal Swedish forest. Ecology 77 (5); 1436-1450.

Smedstad, H. 1997. Branndynamikk i Guttulia Nasjonalpark – en skogshistorisk undersøkelse. Master thesis, Department of Biology and Nature Conservation, Agricultural University of Norway.

Stuiver, M. and Reimer, P. J. 1993. Extended ^{14}C data base and revised Calib 3.0 age calibration programme. Radiocarbon 35; 214-230.

Tryterud, E. 2000. Holocene forest fire history in south and central Norway. Doctor scientiarum theses 2000:11, Agricultural University of Norway.

Turcq, B., Siffedine, A., Martin, L., Absy, M. L., Sounies, F., Suguio, K. and Volkmer-Ribiero, C. 1998. Amazonia rainforest fires: a lacustrine record of 7000 years. Ambio 27 (2); 139-142.

Wardle, D. A., Zackrisson, O. and Nilsson, M-C. 1998. The charcoal effect in boreal forests: mechanisms and ecological consequences. Oecologia 115; 419-426.

Whitlock, C. and Millspaugh, S. 1996. Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. The Holocene 6, 1; 7 – 15.

Zackrisson, O. 1977. Influence of forest fires on the north Swedish boreal forest. Oikos 29; 22-32.

Zackrisson, O., Nilsson, M-C. and Wardle, D.A. 1996. Key ecological function of charcoal from wildfire in the boreal forest. Oikos 77; 10-19.

Personal comment

Söderman, M. Engineer, Ångström Laboratory. Box 543, 751 21 Uppsala, Sweden.

Appendix

The ground- and field layer vegetation in the sample plots. Occurrence is marked with an X.

Species	Stand		
	Pinus-Cladina	*Pinus-Vaccinium*	*Picea*-herb
Actaea erythrocarpa			x
Arctostaphylos uva-ursi	x		
Calluna vulgaris	x	x	
Calypso bulbosa			x
Cetraria islandica	x		
Cladina arbuscula	x	x	
Cladina rangiferina	x	x	
Convallaria majalis			x
Deschampsia cespitosa			x
Deschampsia flexuosa		x	
Dicranum sp.	x	x	x
Empetrum nigrum	x	x	
Epilobium angustifolium			x
Equisetum sylvaticum		x	
Galium triflorum			x
Geranium sylvaticum			x
Goodyera repens			x
Gymnocarpium dryopteris			x
Hylocomium splendens		x	x
Ledum palustre		x	
Linnea borealis		x	x
Luzula pilosa			x
Lycopodium annotinum			x
Maianthemum bifolium			x
Matteuccia struthiopteris			x
Melampyrum pratense		x	
Melampyrum sylvaticum			x
Melica nutans			x
Moneses uniflora			x
Paris quadrifolia			x
Peltigera aphthosa		x	x
Phegopteris connectilis			x
Pleurozium schreberi	x	x	x
Polytrichum commune		x	x
Pyrola minor			x
Ribes spicatum			x
Roegneria canina			x
Rubus chamaemorus		x	
Rubus idaeus			x
Rubus saxatilis			x
Solidago virgaurea			x
Sphagnum sp.		x	
Trientalis europaea			x
Vaccinium myrtillus	x	x	x
Vaccinium uliginosum		x	
Vaccinium vitis-idaea	x	x	x
Viola riviniana			x