A high resolution analysis of macroscopic charcoal deposited in peat

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ABSTRACT

The amount of macroscopic charcoal in the top 25 cm of three cores from a peat land in Hornsö Ecopark, south-eastern Sweden, was compared to the dendrochronology inferred fire history of the site. Because of the occurrence of a recent fire *ex-situ* (1999) and one fire *in-situ* inferred by three fire scared Scots pines, *Pinus sylvestris*, adjacent (5-10 m) to the peat cores, the site provided an excellent opportunity to compare the abundance of charcoal deposited in a peat land after fires *in-situ* and *ex-situ*.

The objectives of the study were threefold: 1) to investigate the relationship between numbers of charcoal fragments (#/cm^3) and measured fragment area (mm^2/cm^3); 2) to test if the smaller size classes could be excluded without changing the signal from the charcoal profile significantly; and 3) to compare the abundance of charcoal deposited between a fire *in-situ* and *ex-situ*.

The number of charcoal fragments and the measured charcoal area exhibited a highly significant correlation ($P < 0.001$ in all three peat cores). When comparing the total number of charcoal fragments > 0.28 mm with those > 0.50 mm in diameter the same charcoal peak pattern emerged. The two size classes also showed a highly significant correlation ($P < 0.001$ in two and $P < 0.05$ in one of the cores). Even if ambiguity arose concerning which charcoal peak that should represent the fire of 1908, the fire of 1999 did not produce a clear peak in the charcoal profile.

It was concluded that the parameter "number of charcoal fragments" is preferred over the measured charcoal area in most cases. Even if the > 0.28 and > 0.50 mm size classes exhibited the same charcoal peak profiles one should be cautious to exclude the 0.28-0.50 mm class. The study suggests that fires *in-situ* depose more charcoal in the peat stratigraphy than fires *ex-situ*.

Keywords: Macrocharcoal; Sieving; Dendrochronology; Peat; Forest fires; *In-situ*; *Ex-situ*.

INTRODUCTION

Why is fire ecology of interest and why study fire history?

Since fire is the major natural disturbance in the boreal forest (Wein, 1983; Granström, 1991a) a number of species is dependent either directly on the fire event itself like some species in the plant genera *Geranium* and *Vicia* (Granström, 1991c; Granström and Schimmel, 1993), or on the structures produced by fires (Rowe, 1983). Thus the elimination of fire regimes has created a threat to many species (Esseen *et al.,* 1997) and a need to mimic or re-establish a natural fire regime (Linder *et al.*, 1997; Nilsson, 2001; Nilsson and Huggert, 2001). This especially applies to the area examined in this study (Nilsson, 2001; Nilsson and Huggert, 2001) (see under Study site in the Method section).

Consequently, there is a need to know how the natural fire regime looked like in different regions and forest types. Dendrochronology or year-ring analysis, has proven to be an accurate method to elucidate the temporal and spatial distribution of fires. But, forest use and wood decay has led to a scarcity of the wood samples needed for the analysis. Due to this, the existing dendrochronological studies only concern at maximum the last four to five centuries (*e.g.* Zackrisson 1977, Engelmark 1984 in northern Sweden; Niklasson and Drakenberg 2001, Niklasson *et al.* 2002, Wäglind 2005 and Niklasson *et al. in prep.* in southern Sweden). The problem with few samples especially applies to southern Sweden where the influence of humans has been more extensive and prolonged than in northern Sweden (Granström, 1991b; Niklasson et al, *in prep.*). Since there seems to have been a higher frequency of fires in the south compared to the north of Sweden (Granström, 1993) there is a possibility that the elimination of fire has struck the fire dependent species harder here.

Charcoal analysis complements dendrochronology

Analysis of charcoal in sediments is a useful complement to dendrochronology. Even though charcoal analysis will probably never achieve the precision of tree-ring analysis when it comes to dating and deciding spatial distribution of fires, the record given by charcoal analysis can stretch back several millenia (*e.g.* Clark 1989; Long *et al.*, 1998; Ohlson and Tryterud, 1999; Pitkänen *et al.*, 2001, 2002, 2003a, 2003b; Carcaillet *et al.*, 2007).

How does charcoal analysis work?

Charcoal analysis is based on small charcoal fragments that are produced by a forest fire and spread by wind and water to a basin, *e.g.* a lake or mire where they deposit (Patterson *et al.*, 1987). The charcoal fragments are very resistent to decay and they are preserved in the sediments where they can be analysed (Komarek 1973 in Patterson *et al.* 1987).

The development of charcoal analysis – area vs. particle number

The development of charcoal analysis is reviewed by Patterson *et al.* (1987) and is summarized in the following section. The disciplin emerged when Johannes Iversen in the 1930s and 1940s noticed charcoal particles in the microscope as he was counting pollen (Iversen, 1934 in Patterson *et al.*, 1987). The first diagram with charcoal quantified (number of charcoal fragments) was presented by Iversen in 1941 (in Patterson *et al.*, 1987) along with his "landnam" theory. Waddington (1969 in Patterson *et al.*, 1987) was the first to quantify charcoal by area. Today, these two parameters seems prevailing when it comes to quantifying charcoal fragments in sediments (Weng, 2005). Examples on studies during the last 20 years that use either area or number of charcoal particles as parameters are shown in table 1. According to a study by Weng (2005), counting area is a better parameter than number of particles since it can be converted to a volume proxy. However, counting area is much more time consuming than counting number of fragments (D. Ventorp, *pers. obs.*). If there is a good correlation between area and frequency of charcoal fragments the pattern of the obtained charcoal series would be similar and the extra effort to measure area could be questioned.

Table 1. Examples on charcoal studies using either area or number of particles as parameters quantifying the amount of charcoal.

Area	Number of particles
Clark, 1988b	Millspaugh and Whitlock, 1995
Clark, 1989	Björkman and Bradshaw, 1996
Clark, 1990	Whitlock and Millspaugh, 1996
MacDonald et al., 1991	Long *et al.,* 1998
Clark and Royall, 1995	Ohlson and Tryterud, 1999
Clark and Royall, 1996	Laird and Campbell, 2000
Pitkänen *et al.*, 1999	Millspaugh *et al.*, 2000
Pitkänen *et al.*, 2000	Tryterud *et al.*, 2000
Tinner *et al.*, 1998	Long and Whitlock, 2002
Tinner *et al.*, 2000	Lindbladh *et al.*, 2003
Carcaillet *et al.*, 2001	Pitkänen *et al.*, 2003b
Carcaillet *et al.*, 2007	Higuera *et al.*, 2005
	Ohlson *et al.*, 2006

The developmen of charcoal analysis – size fractions

It is important to know how large charcoal particles one can use and which mesh size that should be used when sieving the sediment without loosing the discernible charcoal peaks of the obtained charcoal profile. Since there seems to be a negative correlation between size and number of charcoal particles, the smaller size of particles included in the analysis the more time and effort would have to be spent to tally the charcoal particles (Whitlock and Millspaugh, 1996; Clark *et al.* 1998).

The development of charcoal analysis – micro vs. macro

As reviewed in Patterson *et al.* (1987), earlier studies did not get any congruent results when comparing the abundance of charcoal and known or believed fire history. The model by Clark (1988a) constitutes a milestone in the disciplin of charcoal analysis. Clark (1988a) made a difference between charcoal found on pollen slides (commonly refered to as microscopic charcoal with fragments with 0.005-0.080 mm in diameter) and thin-sections charcoal (0.05-10 mm). I use the term macrocharcoal to denote charcoal received from the thin-section method (Clark, 1988b), the Oregon sieving method (Millspaugh and Whitlock, 1995; Whitlock and Millspaugh, 1996) or methods reassembling those mentioned (charcoal fragments > ≈ 0.05 mm in diameter). The charcoal found on pollen slides will be termed microscopic charcoal, < ≈ 0.05 mm (cf. Patterson *et al.*, 1987; Peters and Higuera, 2007). Clarks model (1988a) hypothesised that microscopic charcoal particles are less inclined to be lifted up by wind but once they have they will stay longer in the air. Thus, they could be transported for longer distances. For macroscopic charcoal particles it is the other way around. This means that microscopic charcoal particles will be transported for longer distances and thus derive from a regional source while macroscopic charcoal originates from a more local source. The terms "local" and "regional" is often used in the literatur of charcoal analysis (*e.g.* Carcaillet *et al.* 2001) without proper definitions. Asselin and Payette (2005) refer the local scale to fires within the watershed of a lake and fires outside the watershed to regional fires. In this study, I use the term "local fires" to denote fires within the nearest couple hundreds of meters (< 1 000 m) from the cored site. Thus, "regional fires" refer to fires that are located more than 1 000 m from the site studied. Many studies have confirmed Clark's (1988a) model (MacDonald *et al.*, 1991; Clark and Royall, 1995; Tinner *et al.*, 1998; Carcaillet *et al.*, 2001;), even if at least one conflicting study exists (see Pitkänen, 2000).

In-situ vs. ex-situ fires

However, these studies were based on charcoal from lake sediments. The empirical foundation of charcoal analysis in small peat hollows is not as strong (but see Higuera *et al.*, 2005) and needs to be strenghtened or even revised (see Pitkänen *et al.*'s (2001) "basin-based approach" where they tallied visable charcoal layers instead of individual charcoal fragments). One important difference between lake and peat sediment is the fact that a fire can burn over the peat basin but not over a lake. Studies made on experimental fires indicate that there are significant differences in the amount of charcoal left inside and outside a burnt area, respectively, and that the amount of charcoal declines rapidly with a distance of 1-20 m from the boundary of the fire (Clark *et al.*, 1998; Ohlson and Tryterud, 2000; Lynch *et al.* 2004). Thus, there is reason to believe that a fire that has burnt over the place where the peat core sample is taken will leave considerably more charcoal than a fire that has not burnt over the sample site.

An excellent opportunity

In 2003, Niklasson *et al.* (*in prep.*) studied the Hornsö area, southeastern Sweden, and came across an area where a small fire had burnt ca. 2 hectares in 1999. The fire caused scars in a number of trees in the vicinity of a peat land. As the approximate extension of the fire in 1999 was known and because there was a suitable coring point in the vicinity of the fire, the area looked promising for a charcoal analysis. A more thourogh examination of the site in 2006 revealed a couple of fire scarred trees on the peat land itself. In the field those scars seemed to originate from a fire in the early 20th century. This provided an excellent opportunity to study the abundance of charcoal deposited in a peat land after an *in-situ* (*i.e.* a fire that has crossed over the sample site) and an *ex-situ* fire (*i.e.* a fire that has not burnt over the sample site).

The aims of the study

In this study I want to investigate: 1) if there is a correlation between number of fragments (#/cm3) and measured charcoal fragment area (mm^2/cm^3); 2) if smaller charcoal fractions (for instance charcoal 0.28-0.50 mm in diameter) can be excluded without changing the signal from the charcoal profile significantly; 3) if the amount of charcoal deposited in a peat land differs significantly between *in-situ* and *ex-situ* fires.

METHODS

Study site

The peat land examined is the fringe of the small forest lake Mossgölen in Hornsö Ecopark (57° 01' N; 16° 07' E) in southeast Sweden (Fig 1). Hornsö is considered as one of the most important areas for saproxylic beetles in Northern Europe. The area contains more than 200 red-listed species of wood-living beetles (Nilsson, 2001; Nilsson and Huggert, 2001).

Figure 1. A map with the location of the study site, the Hornsö Ecopark.

Compared to the rest of Sweden the region is characterized by warm and dry summers (Raab and Vedin, 1995). The average temperatures in January and July are -2°C and 18°C, respectively, and the annual precipitation is about 550 mm (Raab and Vedin, 1995). The vegetation zone is hemiboreal (Ahti *et al.*, 1968). This is a transition zone between the boreal zone with mainly Scots pine *Pinus sylvestris*, and Norway spruce *Picea abies*, and the temperate zone with broadleaf species like Pedunculate oak *Quercus robur* and European beech *Fagus sylvatica*.

The peat land cored lies approximately 150 m north of the Mossgölen pond (Fig 2). The peat land is covered with *Sphagnum* spp. mosses and *Rhododendron tomentosum* [former *Ledum palustre* (Almquist *et al.*, 2001)]. Hampered Scots pine and birch *Betula* spp. dominate the overstory (Fig 2). The 27th of July 1999 a low to mid intensive surface fire burnt a ca. 2 hectare area in the vicinity of the cored peat land. About half of the burnt area consisted of a ten year old clear cut and the rest of older pine forest adjacent to the peat core sample site (Nilsson and Huggert, 2001). The fire stopped at the border of the peat land (Fig 3).

Figure 2. The author in action with taking a peat core sample. The shrub layer was dominated by *Rhododendron tomentosum* and *Pinus sylvestris* and *Betula* spp. dominated the overstory. The fire of 1999 stopped at the border of the peat land and the ridge seen in the background.

Field work

The field work was performed during the 2nd of October 2006. With a 9.0 cm diameter, 100 cm long Russian peat sampler (Jowsey, 1966) three peat cores were collected in line at 10, 20 and 30 m from the still visible boundary of the 1999 year's fire (Fig 3). The cores will later be referred to as C30, C20 and C10 as in core 30, 20 and 10 m from the boundary of the fire in 1999. The seven years that have passed since the fire in 1999 could be advantageous since a study of charcoal accumulation in deepwater sediments showed that it could take 4-5 years before differences between *in-situ* and *ex-situ* fires appear (Whitlock and Millspaugh, 1996). Because of the low probability to find appropriate wood samples for tree-ring analysis in normal production forest in southern Sweden the search was concentrated to the area within the boundaries of the Hornsö Ecopark. Consequently, the area within ca. 300 m west and south from the peat core sample area was searched for wood samples, either with fire scars for obtaining years of fire, or older trees to assist in the cross dating process. The RT90 (Swedish National Grid 1990) coordinates of C20 and wood samples nr 9 and above were determined with a GPS receiver, GARMIN GPSmap 60Cx. C30 and C10 were given coordinates in relation to C20. In order to assign coordinates to wood sample 1-8 the bearing and distance to the closest peat core sample point were measured using a SILVA compass and a 5 m branch.

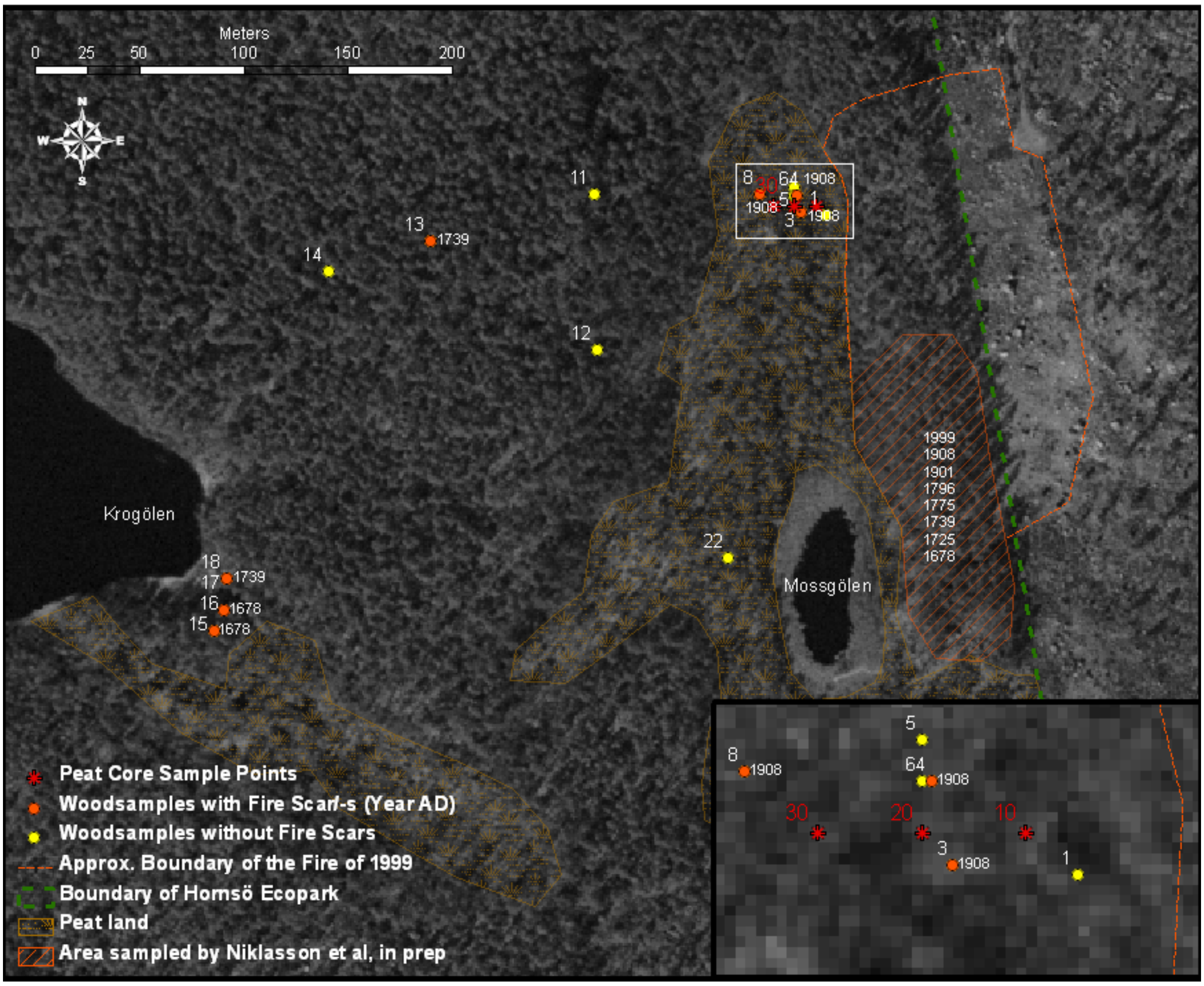

Figure 3. Map over the sample area in the Hornsö Ecopark. The white rectangle denotes the peat core sample area which is magnified in the small window to the lower right. Note that wood sample nr 16 also had a fire scar from 1739 (cf. Table 4) and that the boundary of the fire in 1999 is only approximate. © Lantmäteriverket Gävle 2007. Permission I 2007/2268.

Tree-ring analysis

Tree-ring analysis or dendrochronology is based on the principle that trees with visible annual growth (year-rings), and with similar spatial and temporal spread will display similar response to external conditions such as climate and site conditions in the annual growth (Stokes and Smiley, 1968). For example, a year with a severe drought during the growth season will cause more or less all trees in the region to produce an exceptional narrow ring compared to rings before and after that extreme year. Such a deviant year is called pointer-year (Niklasson, 1998). Combining the pointer-years for a specific area will create a unique sequence often referred to as a master chronology. By comparing the year-ring pattern of a wood sample with the master chronology you are able to date the wood sample if you find a good congruence between the two.

The wood samples that were fragile were first glued on chipboards. All wood samples were then progressively sanded down to paper grade number 600. Tree-rings were counted using a stereomicroscope with x 8-40. Samples were cross dated using a skeleton plot (Stokes and Smiley, 1968) with pointer years achieved from another dendrochronological study in the Hornsö area (M. Niklasson, *pers. comm.*). Niklasson *et al.* (*in prep*) made a tree-ring analysis of the fire history for the whole Hornsö area. One of their sample sites was located 100-200 m from the location where I collected my peat cores (Fig 3). The area and recorded fires are marked in Fig 3.

Macrocharcoal analysis

The top 25 cm of each peat core sample was sliced in 0.5 cm sections. Thus each core was sliced into 50 sections. Because the calibration of the customized slicing device was not successful in the start, the 0.5 cm sections of peat core nr 20 (C20) between 0 and 8 cm are somewhat approximate. I developed a routine to wipe dry the slicing device after each cutting and to wash it after every 10^{th} cutting. One cm^3 (which was suggested to be enough by Carcaillet *et al.* (2001)) from every section was put in 5% NaOH over night before it was gently sieved through 2, 1, 0,5 and 0.28 mm meshes (macroscopic charcoal particles > 0.05 mm in diameter, see Introduction above). The sieved material was put in Petri-dishes and the charcoal fragments were tallied and measured for area using a stereomicroscope x 8-40 with an optical grid. Particles that were jet black, angular and had a shiny surface were assessed as charcoal fragments. But also fragments that were obviously charred, like jet black plant objects that were obviously burnt but lacked the "angular" shape, were included and tallied as charcoal.

Since the peat growth rates (cm peat/yr) of C20 was obtained from the dating analysis performed by Flett Res Ltd, the charcoal concentration in C20 was converted to CHAR, charcoal accumulation rates ($\#/cm^2/yr$). Note that in other studies (e.g. Long *et al.* 1998) sample deposition time (yrs/cm) was used instead of peat growth. I assume that peat growth, if inverted, is the same as sample deposition time. By obtaining CHAR, you get the charcoal accumulation per year instead of per cm (of depth).

To identify local fires the charcoal peaks have to exceed a certain threshold (Clark, 1990). Higuera *et al.* (2005) investigated this threshold for the Moran State Park, Washington, USA and concluded that the optimal threshold for charcoal size class 0.15-0.50 mm was 1.63 to 1.75 times the median for the profile studied. Taking the average of 1.63 and 1.75, I multiplied the median CHAR-value for the > 0.28 size class of the profile in my C20 with 1.69 and the CHAR values exceeding that value was assumed to represent a local fire. The optimal threshold for the charcoal size class 0.50-50 mm was 1.88-2.50 times the median CHAR-value in the same study as used above. Thus the average (2.19) was used for my size class > 0.50 mm.

^{210}Pb-dating of the peat cores

The base of ^{210}Pb-dating is the disequilibrium between ^{210}Pb and ^{226}Ra which both are a part of the ^{238}U decay series. This disequilibrium derives from the diffusion of ^{222}Rn to the atmosphere (Appleby & Oldfield, 1992). A simplification of the process is visualized in Figure 4.

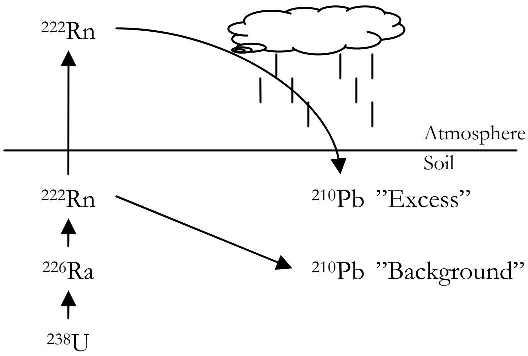

Figure 4. A simplified overview of the ^{238}U decay series.

^{238}U decays in several steps to ^{226}Ra. Since the ^{238}U has a half-life of 4,5 billion years it is considered to be present everywhere in soils over the world and at a constant level of radioactivity. ^{226}Ra is in secular equilibrium to ^{238}U which means that ^{226}Ra shows the same radioactivity as ^{238}U. The result is that ^{226}Ra exists with a constant radioactivity more or less everywhere in the soil (www.flettresearch.ca/Webdoc4.htm). The "daughter" of ^{226}Ra is volatile gas and a fraction of it will diffuse to the atmosphere where it, in just a couple of days, decays via several steps to ^{210}Pb. This ^{210}Pb sooner or later will be deposited in the soil by precipitation and fixed in the soil particles (Appleby & Oldfield, 1992). In the literature this ^{210}Pb is referred to as "excess" or "unsupported" ^{210}Pb. The ^{222}Rn that did not diffuse to the atmosphere, decays in the soil to ^{210}Pb that is referred to as "background" or "supported" ^{210}Pb. A basic assumption for almost all models used for ^{210}Pb-dating is that the post-deposition of the ^{210}Pb or the sediment are negligible (Binford, 1990). If estimates of the background activity can be achieved the excess activity can deduce the age of sediment tested in accordance with the radioactive decay law, which is described below;

$$N = N_0 * e^{-\lambda t} \quad (1)$$

Where N = measured activity, N_0 = initial activity, t = age and λ = the disintegration constant. The formula for λ is;

$$\lambda = \ln 2/\text{half-life of element} \qquad (2)$$

So, in the case of ^{210}Pb with a half-life of 22.3 years, λ is ln2/22.3 ≈ 0.031 yrs^{-1}.

Samples from C20 and C10 were sent for analysis to Flett Research Ltd (Manitoba, Canada; www.flettresearch.ca). The Constant Rate of Supply (CRS) model was used in the analysis to date the core. One of the advantages with this model is that it does not assume a constant rate of sediment accumulation, but only a constant input of ^{210}Pb to the sediment in question. Besides the age of the core this also gives you the sediment accumulation rates at different depths of the core which is essential for adjusting the charcoal concentration into charcoal accumulation rates, CHAR (see under "Macrocharcoal analysis").

Statistical analysis

I used the non-parametric Spearman rank correlation coefficient, r_S, to measure the correlation between the sum of charcoal area and number of charcoal fragments at every 0.5 cm section. The two variables were compared in the three peat cores separately. The reason why I choose the Spearman rank correlation was twofold. First, I was not sure if I could expect a normal distribution or that the charcoal counts could be taken to be independent, and this assumption is supported by Clark (1990). In this case a parametric test should be avoided and Dytham (1999, p. 19) recommends Spearman rank correlation coefficient, r_S or Kendall rank correlation coefficient, τ. Second, although the Spearman and Kendall coefficients are very similar, the Spearman coefficient is recommended when there is a large sample size (Zar, 1999, p. 398). Since my sample size in C30, C20 and C10 were 41, 33 and 18 respectively I chose accordingly. When testing if the correlation is significant the null hypothesis, H_0, is as follows (after Fowler *et al.*, 1998);

H_0: There is no correlation: the value of r_s is obtained by chance and/or sampling error.

The Spearman rank correlation coefficient was also used to measure the correlation between the four size classes of charcoal. Calculations were made in Microsoft Office Excel 2003. The difference of charcoal from an *in-situ* fire compared to an *ex-situ* fire was not estimated by quantitative statistics.

RESULTS

The comparison between the number of charcoal particles and area

I found a highly significant correlation (P = < 0.001) between the number of charcoal fragments (#/cm^3) and area (mm^2/cm^3) for all three cores (Fig 5). The Spearman rank correlation coefficient was 0.960; 0.958 and 0.824 for C30, C20 and C10 respectively (Tab 2). Because of these results only charcoal concentrations (#/cm^3) are considered in the rest of the study.

Table 2. An overview of the statistics for the correlation between numbers (#/cm^3) and measured area of charcoal fragments (mm^2/cm^3) for the three different peat cores.

	C30	C20	C10
r_s	0.960	0.958	0.824
n	41	33	18
$r_{Critical}$	0.501	0.554	0.728
P-value	< 0.001	< 0.001	< 0.001

The comparison between the four different charcoal size classes

Charcoal particles in the > 2.00 mm class were only found in C20 (Fig 6) and particles > 1.00 mm were only found in smaller amounts (maximum ca. 10 #/cm^3 C20 at approx. 14 cm of depth). Therefore only the two smallest size classes were compared. The relationship between size classes > 0.28 and > 0.5 mm showed a significant correlation in all three cores ($P_{C30} < 0.001$; $P_{C20} < 0.001$ and $P_{C10} < 0.05$). An overview of correlation data is shown in Table 3.

Fire history of the study site according to the tree-ring analysis

22 wood samples were collected across the area but only fifteen were successfully dated. Every wood sample besides nr 7 (birch; dating unsuccessful) was from Scots pine. Six of the dated samples (wood samples nr 1-8) were taken in the close vicinity, < 10 m, of the peat samples (Fig 3). Three fires were identified and dated to 1678, 1739 and 1908 (Tab 4). In addition to those three fire years, Niklasson *et al.* (*in prep.*) also found fire scars from 1999, 1901, 1796, 1775 and 1725. The approximate area sampled by Niklasson *et al.* is marked in Figure 3.

The locations of the wood samples reveal that the fire of 1908 actually burnt *in situ* on the peat land where the core samples were taken. This is noteworthy because peat lands are most often considered as fire breaks (Hellberg *et al.*, 2004).

Table 3. An overview of the statistics for the correlation between size class > 0.28 and > 0.50 mm for the three different peat cores.

	C30	C20	C10
r_s	0.800	0.872	0.689
n	41	33	18
$r_{Critical}$	0.501	0.544	0.600
P-value	< 0.001	< 0.001	< 0.05

The fire of 1908 seems to have stopped somewhere close to the western boundary of the peat land since it's not recorded in wood samples nr 11 or 22. This fire was also found by Niklasson *et al.* (*in prep.*) (Fig 3).

Both the fires from 1739 and 1678 seem to have covered a large area since they are found both in my most remote samples and in the area sampled by Niklasson *et al.* (*in prep.*). The fire of 1739 did not burn over the peat core sample area since there is no scar in wood sample nr 5, a tree only ca. eleven years old in 1739 which should either have gotten a scar or died if the fire went by (M. Niklasson *pers. comm.*). Since there were no fire scars in wood samples nr 3, 4 and 8, from 1796, this fire was also assessed to have burnt *ex-situ*. The same seems to be true for the fire in 1775 according to the wood samples nr 5 and 8. Consequently, the fire of 1908 seems to be the only fire *in situ* of the peat core sample area from 1728 (oldest ring of sample nr 5) to the present. In summary; eight fires were dated in the area (300x300 m); 1999, 1908, 1901, 1796, 1775, 1739, 1725 and 1678. From year 1728 to present only the fire in year 1908 seems to have burnt over the site where the peat cores were taken.

Fire history of the study site according to the macrocharcoal analysis

In C30 there are three possible peaks at ca. 16, 17 and 21-22 cm of depths (Fig 6). C20 indicates a fire event at 10-14 cm of depth, a small possible peak at 17 cm and two peaks at ca. 22 and 24 cm of depth respectively. The C10 which in general had a lower number of charcoal compared to C30 and C20, shows a possible peak at 14 cm, a considerable peak at 18 and three peaks at ca. 21, 23 and 25 cm of depth. Hereafter I will refer to the different peaks by writing for example C20: 11 which mean that I am referring to the peak 11 cm of depth in the peat core 20 m from the edge of the fire in 1999.

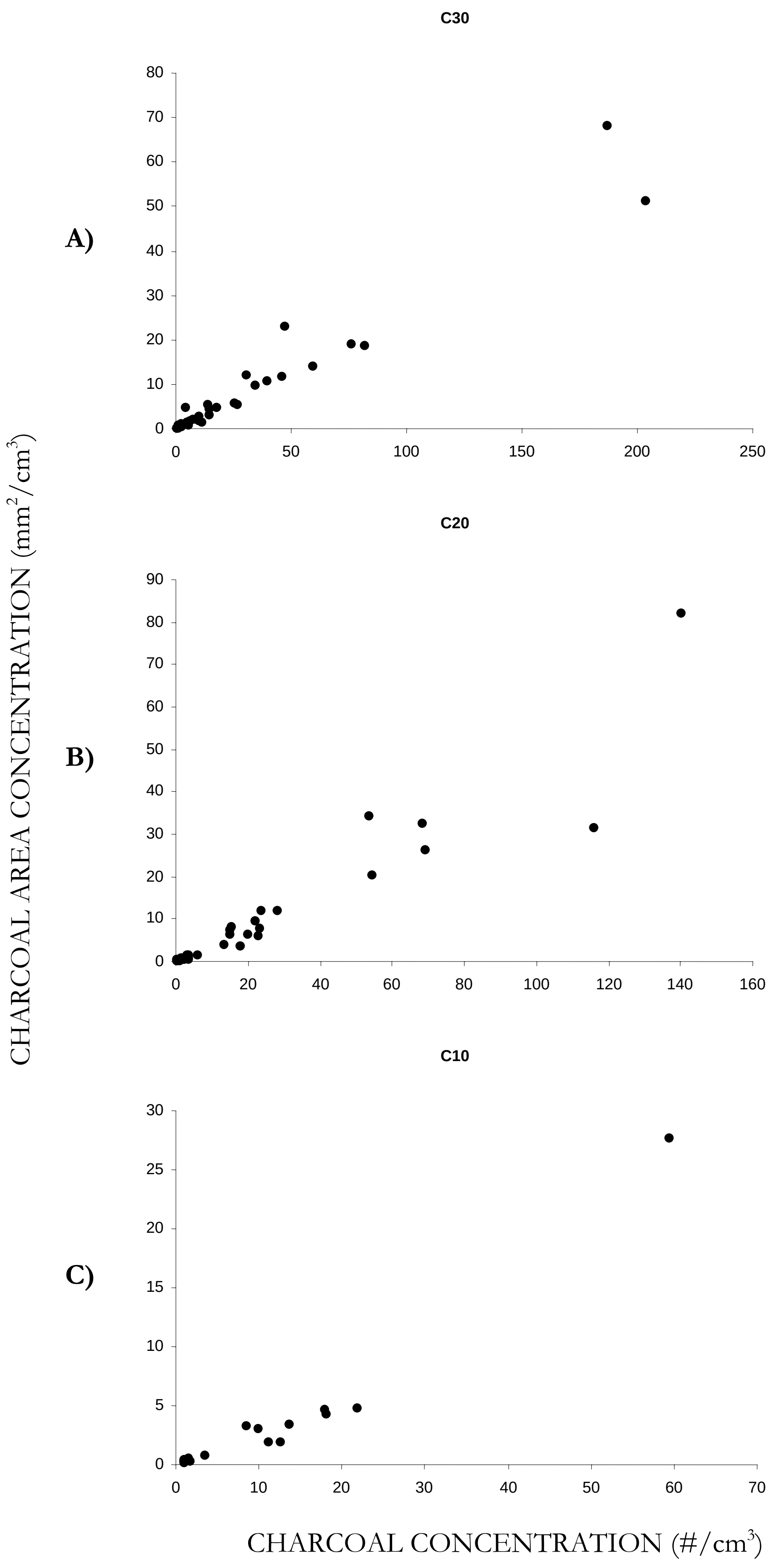

Figure 5. Relation between number and area of charcoal fragments in three peat cores.

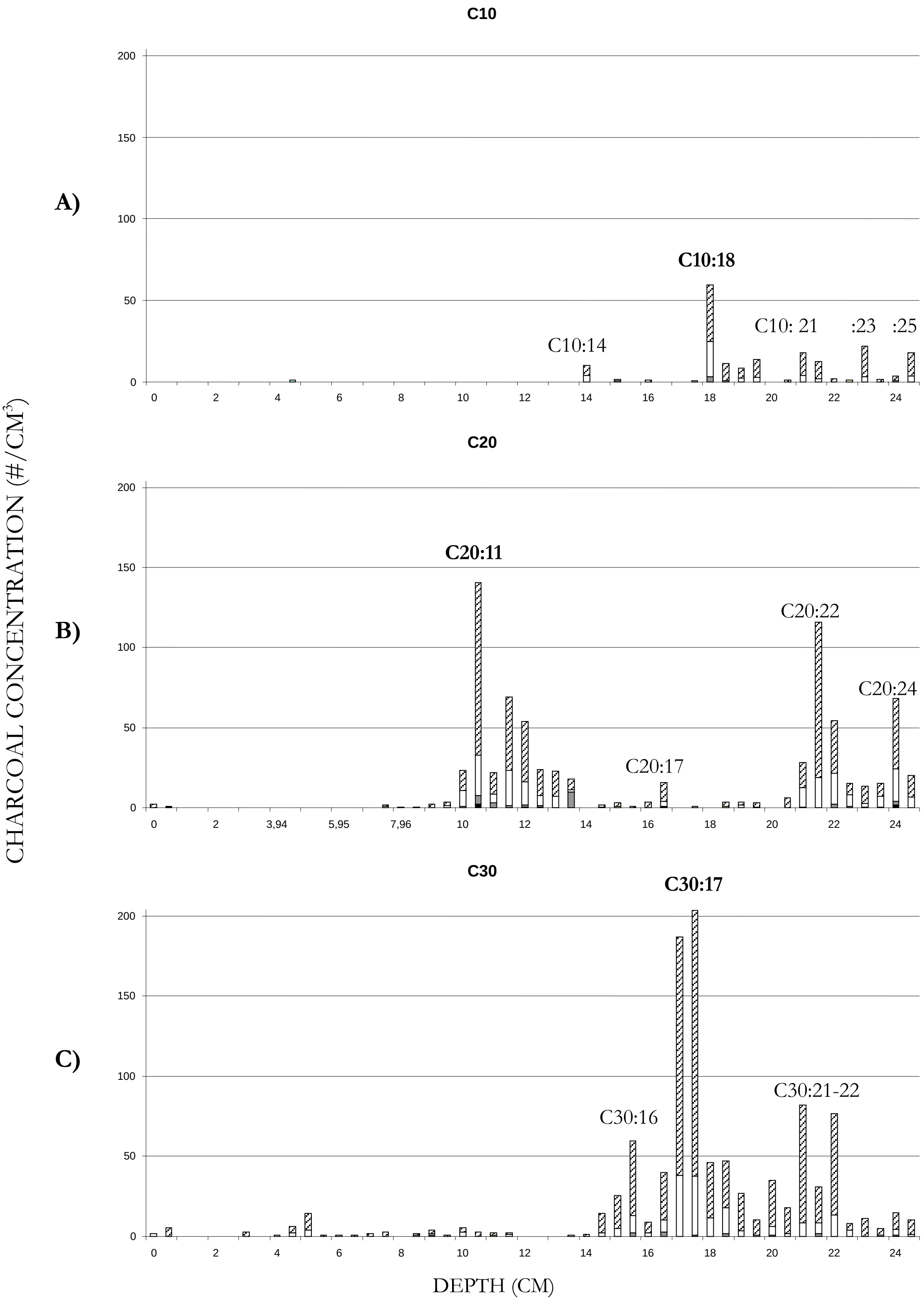

Figure 6. The charcoal concentration at different depths of the three peat cores. Different colours represent different size fractions: Black = > 2.00 mm; grey = 1.00-2.00 mm; white = 0.50-1.00 mm and lined = 0.28-0.50 mm.

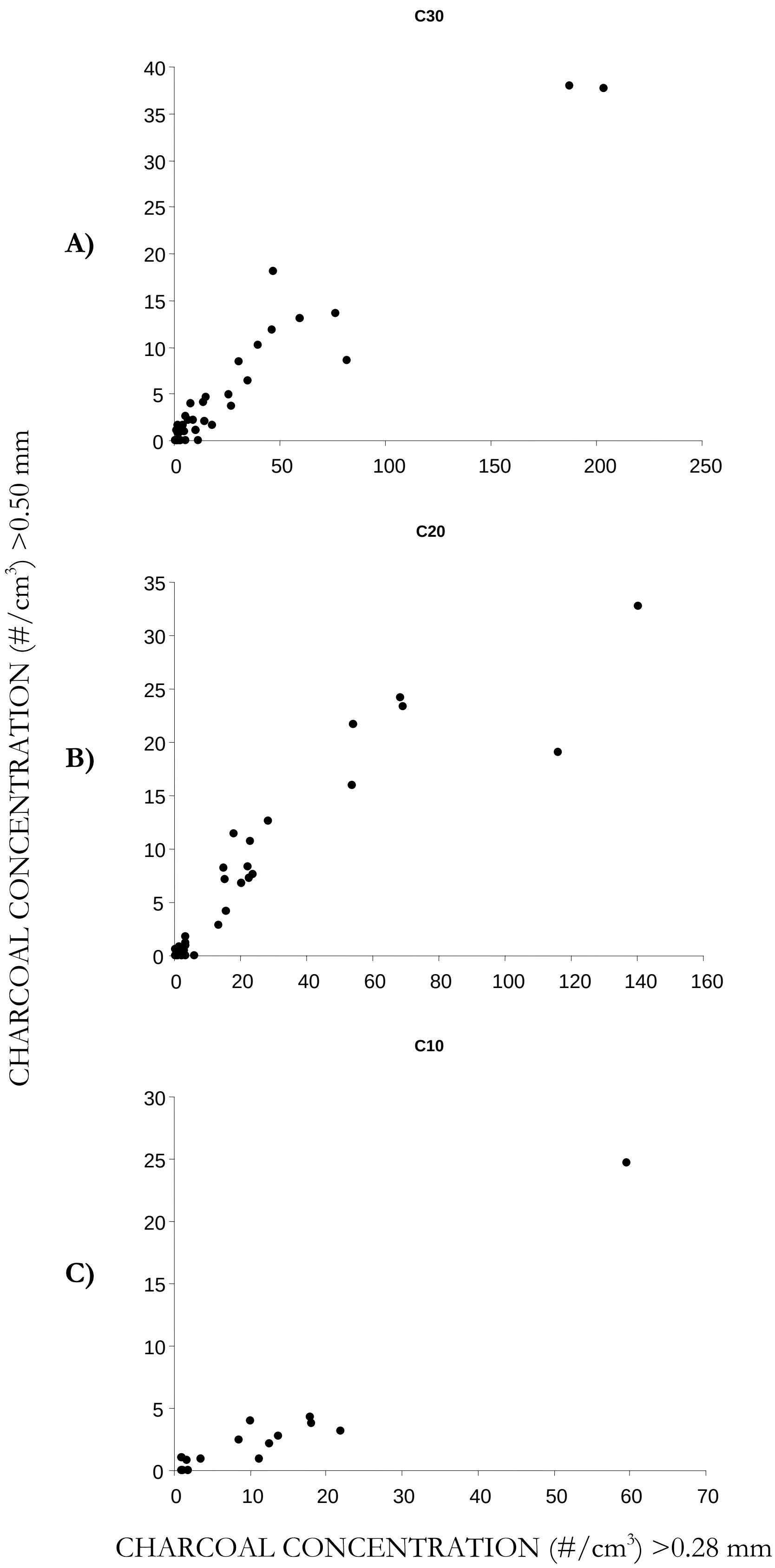

Figure 7. Relation between two size classes of charcoal fragments in three peat cores.

Table 4. Dendrochronologically inferred fire history for the fifteen wood samples that were successfully crossdated. If the oldest ring consists of the pith or not is written after the year of the oldest ring. Wood sample nr 13 had a possible fire scar at 1739.

Sample nr	Oldest Ring (Year AD)		Youngest Ring (Year AD)	Fire (Year AD)
1	1797	Pith	2006	
3	1780	Pith	2006	1908
4	1790	Pith	1960	1908
5	1728	Pith	1984	
6	1920	Pith	2006	
8	1774	Pith	1989	1908
11	1856	Pith	2006	
12	1623	Pith	1792	
13	1695	Pith	1803	1739 (Pos.)
14	1881	Pith	2006	
15	1641	Old.	1828	1678
16	1640	Old.	1865	1678, 1739
17	1689	Pith	1827	1739
18	1690	Pith	1838	1739
22	1770	Pith	2006	

Both C20 and C10 were sent for ^{210}Pb-dating but I only consider the dating with the CRS-model of C20 to be useful for further interpretations. I conclude that the dating of C10 was to uncertain due to problematic data (four different possible scenarios were presented by Flett Res.; App. 1). Thus, CHAR was only calculated for C20.

If all four size classes were included, the median CHAR was 0.629 #/cm^2/yr and the optimal threshold 1.063 (0.629*1.69) #/cm^2/yr according to the method described by Higuera *et al.* (2005) (Fig 8 a). Four charcoal peaks were consequently identified as fire events, namely 1961-1946, 1932-1931, 1908-1899 and 1888-1885 (Fig 8 a). These fire events will be referred to as 1954, 1932, 1904 and 1887 for the sake of simplicity.

When only the three largest size classes were taken into account (charcoal particles > 0.5 mm in diameter) the median CHAR was 0.330 #/cm^2/yr and the optimal threshold 0.724 (0.330*2.19) #/cm^2/yr (Fig 8 b). This also leads to the identification of four peaks as fire events, namely 1961-1952, 1947-1946, 1905-1899 and 1888-1886. These fire events will hereafter be referred to as 1957, 1946, 1902 and 1887. When comparing the CHAR peaks between > 0.28 and > 0.50 mm, note that the peak in Figure 8 a that was identified as a fire event in 1932-1931, was not considered to be a fire event in Figure 8 b and that the fire event of 1961-1946 was divided into two fire events, 1961-1952 and 1947-1946 (Fig 8 b).

Thus, the difference in the macrocharcoal analysis between considering > 0.28 and > 0.5 mm charcoal particles constitutes whether there was a fire event ca 1932 and if the charcoal peak between the 1940s and 1950s represents one (1954) or two (1957 and 1946) fires.

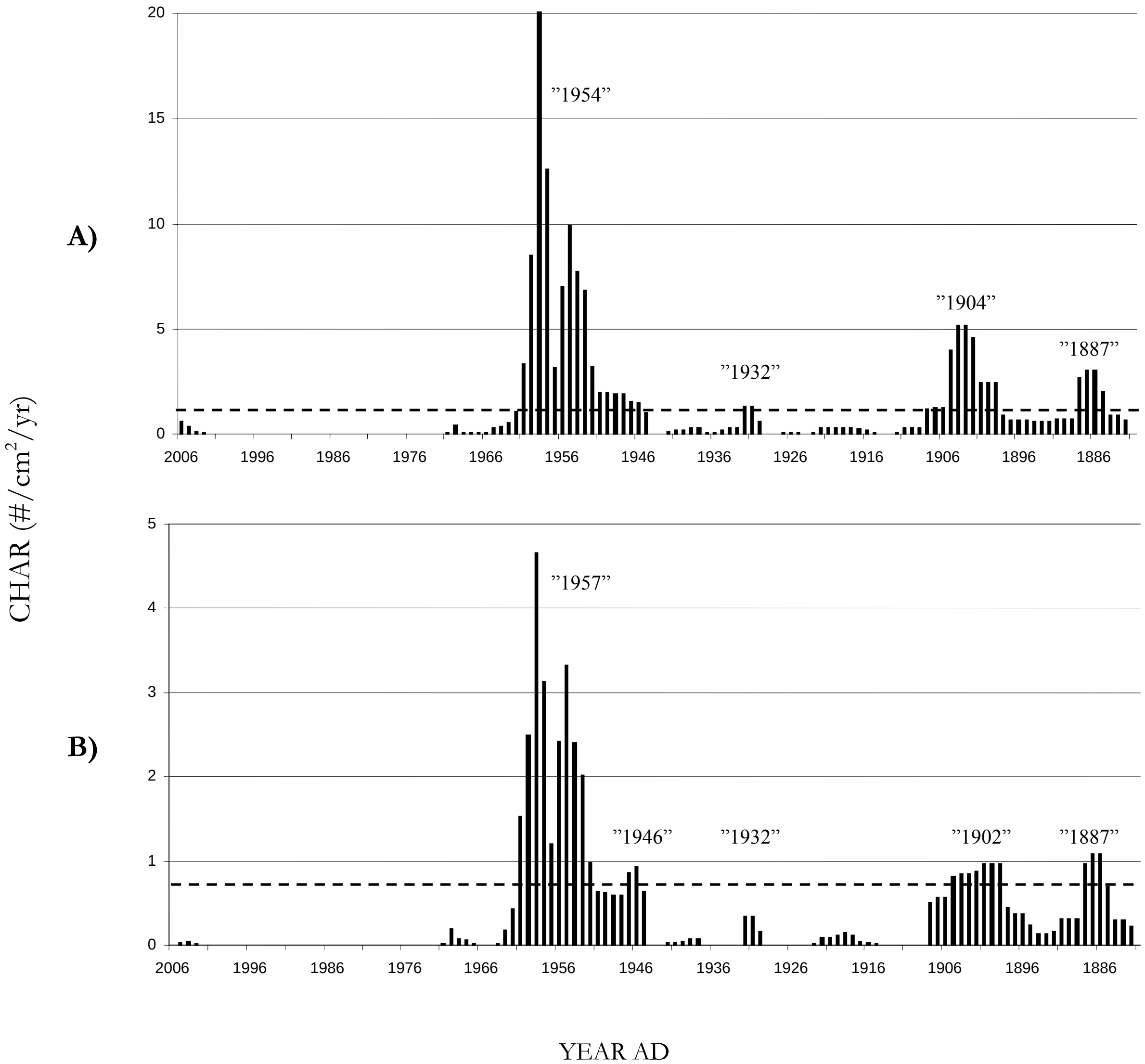

Figure 8. The charcoal accumulation rates (#/cm²/yr) for peat core nr 20. A) All charcoal particles > 0.28 mm included. B) All charcoal particles > 0.50 mm included. The dashed line represents the calculated optimal threshold according to the method described in Higuera *et al.* (2005). Charcoal peaks reaching above this line are considered to be a fire event.

The comparison between individual fires in-situ and ex-situ

The fire in 1999 that stopped 10-30 m from the peat core sample points did not spread noticeable amounts of charcoal fragments (Fig 8). The amount of charcoal found in the top of the cores does not seem to exceed the amount of charcoal received from the regional source (Clark and Royall, 1995).

The fire event that was dated to 1904 or 1902 corresponds well with the fire dated to 1908 by the tree-ring analysis (Fig 8). If considering the peak in 1904 and 2006 a rough estimate is that a fire *in-situ* leaves about ten times as much charcoal particles as a local but *ex-situ* fire.

DISCUSSION

Number of particles vs. area

The general strong correlation between macroscopic charcoal concentration ($\#/cm^3$) and charcoal area concentration (mm^2/cm^3) (Fig 5, Tab 2) are in accordance with Patterson *et al.* (1987). With data from a site on the isle of Arran in Scotland they found a significant correlation (Pearson product-moment correlation coefficient, $r = 0.980$, D.F. = 10, $P < 0.001$) between the number of charcoal fragments and charcoal area in microscopic charcoal. Also Earle *et al.* (1996) had a consistency between the two parameters (no statistics were calculated) in a charcoal study in Alaska, USA. As the larger particle size classes did not exhibit the same pattern as the smaller ones, they suggest that estimates of total charcoal area is more sensitive than particle number due to the random variations of the larger, more infrequent particles.

Recently, Weng (2005) showed that area is a better measure than number of fragments if it is converted to volume by the formula;

$$V = C\sum A^{3/2} \tag{3}$$

Where V is volume, C is a constant and A is area. However, in a comparison between the three parameters ($\sum A$, $\sum A^{3/2}$ and number of particles) in a core by Weng (2005) the same charcoal peaks were visible (they differed in size though) in all the three profiles. That is, although the height of the peaks differed within and between core profiles the same numbers of charcoal peaks were seen independent of parameter used. Therefore I argue that number of charcoal fragments will often be enough to get charcoal peaks corresponding to fire events.

One should not confuse area with the volume proxy. As shown in my study numbers and area of charcoal particles are strongly correlated. Charcoal area becomes a more stable and accurate parameter first when it has been converted to the volume proxy. Thus, the extra effort made in studies using area, not converted to the volume proxy (*e.g.* Carcaillet *et al.*, 2007) can be questioned. If the area instead was converted to the volume proxy the extra labour would be more defendable.

The size classes

My study suggests that the charcoal profiles considering charcoal particles > 0.28 mm and > 0.50 mm will exhibit the same overall pattern, inferring that tallying charcoal particles < 0.50 is not necessary for getting reliable charcoal profiles (Fig 5). These results are supported by Lindbladh *et* *al.* (2003) who used almost the same size classes (> 2.00; 2.00-1.00; 1.00-0.50 and 0.50-0.25 mm). Similar results were also found by Higuera *et al.* (2005) when they compared the CHAR of the charcoal particle classes 0.15-0.50 and 0.50-50 mm in diameter. These two classes had a significant correlation (Pearson $r_{\text{all sites combined}} = 0.849$, P « 0.01, n = 738). Note that they tested the correlation on the CHAR values and had two distinct classes (0.15-0.50 and 0.50-50, not > 0.15 and >0.50 mm in diameter). However, they put forward a disadvantage with only using the larger size class. The larger size class had an almost twice as big false-positive rate, which means that the 0.50-50 mm class identified almost twice as many false fires (fires that did not occur) compared to the combined 0.15-50 mm class.

Another study that presented resemblance among size classes is the one by Whitlock and Millspaugh (1996). All their three size classes; 0.063-0.125, 0.125-0.250 and > 0.250 mm in diameter displayed a similar pattern (no statistic test was done). However, they noted that the largest size class of charcoal particles, > 0.250 mm, contained to low numbers, ranging from ca. 5-25 charcoal particles per cm^2. This range is in accordance with the size class > 0.50 mm (ranging from 0 to ca. 40 charcoal particles per cm^3) in my study. Earle *et al.* (1996) got congruence among different size classes when an average of 40-80 charcoal particles was tallied per size class. Thus, considering my study the low numbers of particles in the larger size classes argues for an inclusion of the 0.28-0.50 mm class.

When Carcaillet *et al.* (2001) tested the correlation between size classes (ranging from ca. 0.12-1.70 mm), all classes < 0.60 mm in diameter were strongly correlated with the total charcoal concentration. Thus charcoal particles < 0.60 mm contribute the most to the total charcoal concentration.

Consequently, based on the studies cited above, I would call upon caution when excluding the size class smaller than 0.50 mm (where the minimum is ca. 0.15-0.28 mm) even if the charcoal profiles from the size classes > 0.28 and > 0.50 mm will exhibit the same pattern. This conclusion is further supported by Earle *et al.* (1996) who conclude in their study that the interpretation of the charcoal series should rely on data from the < $10^{5.5}$ μm^2 class (this class is comparable to my 0.28-0.50 mm class). Thus, to include the 0.28-0.50 mm class in the charcoal analysis will be a good compromise between reliability and effort.

Fire dates according to dendrochronology and ^{210}Pb-dated profiles

According to the tree-ring analysis only two fires (the fire of 1999 not included) occurred in the area during the 20^{th} centaury. One in 1908 that evidently went over the cored site and one in 1901 in the area close to the sample site. The ^{210}Pb-dated charcoal profile on the other hand identifies fire events ca. 1950 and in the 1900s, possibly one in the 1930s. Thus, the results from the tree-ring analysis and the ^{210}Pb-dated charcoal profile of C20 do not exhibit congruence. I recognize two explaining scenarios;

1) The ^{210}Pb-dating of C20 is correct; the tree-ring analysis has "missed" a fire event in the 1950s, possibly in the 1930s and 1887.
2) The dendrochronological analysis is accurate; the ^{210}Pb-dating has underestimated the age of the core.

Assuming that the ^{210}Pb-dating of C20 is correct the year-ring dated fire of 1908 corresponds very well with peak C20:21-22 identified as fire events in 1904 and 1902 in the CHAR profiles, > 0.28 and >0.50 mm respectively (Fig 6 and 8). Note that after ca. 80-100 years the age estimates can become quite imprecise due to small changes of the estimated ^{210}Pb background (Binford, 1990; R. Flett *pers. comm.*). However, the three peaks ca. 1950, 1932 and 1887 lack support from the tree-ring analysis. Even if I exclude the low peak C20:17 (1932) and only consider the CHAR profile of size class > 0.50 mm and call C20:24 (1887) a false-positive, it is hard to explain the considerable peak C20:10-14 (1954 and 1957) (Fig 8). The absence of fire scar in wood sample nr 6 (taken 5.5 m away from C20, pith dated to 1920 [Fig 3, Tab 4]) is a firm evidence against a fire here in the 1950s. The wood sample nr 6 even supports the exclusion of C20:17 (1932) since the tree would most likely have died if there was a fire here in the 1930s. The only other explanation would be that I have encountered the remaining of a human made camp fire. However, I find this scenario highly unlikely.

Scenario nr 2 seems more reliable. The average peat growth rate in C20 is about 0.2 cm per year according to the ^{210}Pb-dating, which means that 10 cm of depth represents approximate 50 years and 20 cm 100 years. This value seems a bit high compared to other studies (Tab 5). When comparing the charcoal profile with the dendrochronological data I estimate the peat accumulation rate to 0.1 cm/yr (Fig 9). This would be a reasonable (but sometimes still high) estimate if conferring the average accumulation rates found in other studies (Tab 5). Especially the study done by Økland and Ohlson (1998) is of importance because it is based on 13 mires across Sweden, where the peat was dated with the "pine method" (described in Ohlson and Dahlberg, 1991). Besides getting an average peat growth rate of 0.06-0.10 cm/yr they also showed that this figure could vary between ca. 0.01-0.30 cm/yr. But their average does support my estimate. Even Higuera *et al.* (2005) recorded a peat site with an average accumulation rate of 1.03 cm/yr. Thus, the inferred peat accumulation rate by ^{210}Pb-dating is not impossible but looking at the averages from several other studies, my estimate based on the dendrochronological dated fire events, seems more likely.

Table 5. A selection of the estimated average peat accumulation rates for a number of studies.

Study	Country	Average Peat Accumulation Rate (cm/yr)
Økland and Ohlson, 1998	Sweden	Ca. 0.06-0.10
Pitkänen *et al.*, 2001	Finland	0.013
Pitkänen *et al.*, 2002	Finland	0.011
Tryterud, 2003	Norway	0.048
Higuera *et al.*, 2005	USA	0.100
This study	Sweden	0.200*

* According to the ^{210}Pb-dating by Flett Res Ltd.

To keep the variation of peat growth at different depths I simply halved the peat accumulation rates, derived from the ^{210}Pb-dating, in every section of the peat core (C20). Using the same procedure presented earlier the optimal threshold was 0.695 #/cm^2/yr (Fig 9). Thereby assuming an average peat growth of 0.1 cm/yr the identified fire events from Fig 8 b 1957, 1946, 1902 and 1887 then corresponds with 1907 (1916-1898), 1886 (1888-1884), 1797 (1803-1791) and 1767 (1770-1764) respectively in Fig 9. The fire event "1907" would correspond to the fires in 1908 and 1901 (this could explain why there seems to be two peaks in that event). It is interesting that a fire event is identified around 1887 in both scenarios (Fig 8 b and 9) even though it lacks support from the tree-ring analysis. I have no explanation for this other than it is reasonable to believe that this peaks is a false-positive or that a fire actually occurred in the 1880s without leaving any fire scars. The small peak at year 1932 in Figure 8 b is equivalent with the year 1856 in Fig 9. This could be corresponding with a large fire in 1868 that covered ca. 400-700 ha within the Hornsö area (but not in the vicinity of the sampled area in this study) (Niklasson *et al.*, *in prep.*). Large and intense fires can without doubt occasionally spread macroscopic charcoal fragments for several kilometres (Tinner *et al.*, 2006). The fire events of 1797 and 1767 in Figure 9 would consequently correspond with the tree-ring dated fires of 1796 and 1775, respectively.

The fire in-situ (1908) and the fire ex-situ (1999)

Besides the ^{210}Pb-dating the macrocharcoal analysis in this study is associated with more uncertainties. First, one regards the use of Higuera *et al.*'s (2005) method to deduce the optimal threshold for the CHAR-values. The method is only considered to be effective to detect fires of high intensity whereas the fire regime in Scandinavia is characterised by low intensity fires. Second, Niklasson *et al.* (2002) suggest that charcoal data from peat tend to miss

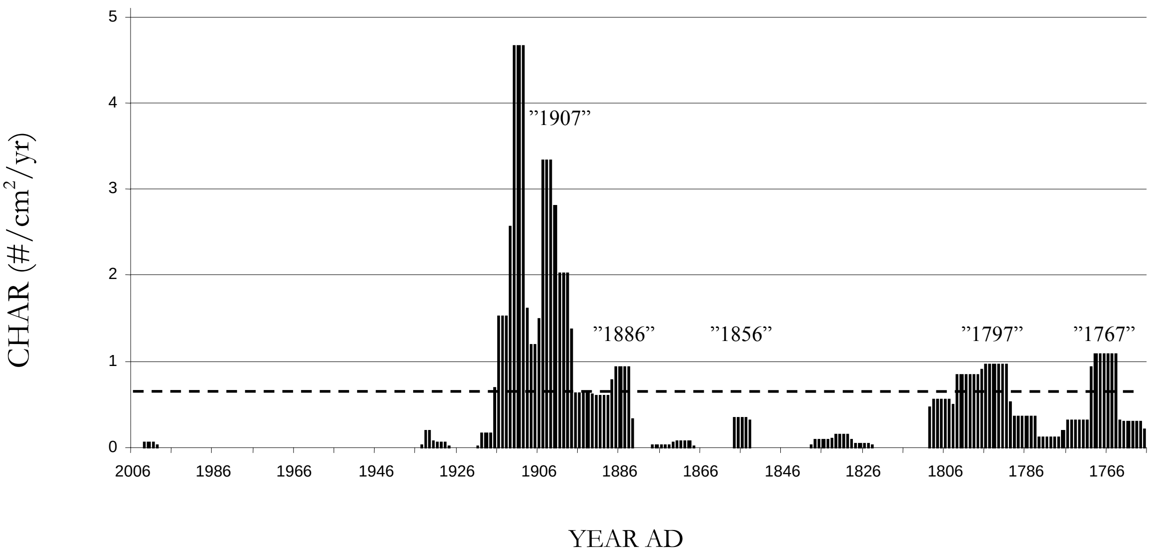

Figure 9. The charcoal accumulation rates (#/cm^2/yr) for peat core nr 2. All charcoal particles > 0.50 mm are included and the peat accumulation rate is estimated to 0.1 cm/yr on the basis of a comparison of the dendrochronological data and the charcoal profile. The dashed line represents the calculated optimal threshold according to the method described in Higuera *et al.* (2005). Charcoal peaks reaching above this line are considered to be a fire event.

fires of low intensity. Fires seem to have a highly patchy pattern which leads to a variable burning intensity over the burnt area (Ohlson and Tryterud, 2000; Ohlson *et al.*, 2006). Despite the differences in methodology between Ohlson and Tryterud (2000) and Ohlson *et al.* (2006) they conclude that the risk of “missing” a fire when only sampling one point is about 15 %, even within a burnt area. This could explain the conclusion by Niklasson *et al.* (2002) since they relied on one core only (examined by Björkman and Bradshaw (1996)) where the recorded charcoal peaks did not correspond to a number of fires inferred by tree-ring dated fire scars.

Since I have three peat sample points and three dated fire scars from 1908, I conclude that it is highly unlikely that the fire from 1908 would not have been recorded in at least one of my peat cores. Furthermore, I assume that the charcoal peaks C30:17, C20:11 and C10:18 (Fig 6) represent the fire of 1908 and possibly 1901. If that is the case my study suggests that fires that burn *in-situ* leave considerably more charcoal than a fire that that burnt *ex-situ*. This suggestion is based on the different amplitudes of the fire events 1954 in Figure 8 a or 1957 in Figure 8 b and their corresponding peaks in Figure 6 compared to the amount of charcoal in the top of the cores (0-2 cm of depth in Figure 6 and ca 2006-1996 in Figure 8). However, keep in mind that one of my underlying assumptions when identifying the 1908 fire is that it would have a considerable larger peak than the rest because I knew it had burnt *in-situ*. Making the conclusion that *in-situ* fires leave more charcoal is consequently a result of my own assumption leading to circular argumentation. Several studies of experimental fires have nevertheless shown that *in-situ* fires leave more charcoal than *ex-situ* ones (Clark *et al.*, 1998; Ohlson and Tryterud, 2000; Lynch *et al.*, 2004) and several others support the idea of larger charcoal peaks the closer the area burnt (Whitlock and Millspaugh, 1996; Blackford, 2000; Gardner and Whitlock, 2001; Gavin *et al.*, 2003). My study shows without ambiguity is that the fire of 1999 which stopped just 10-30 m away from the peat core sampling points has not caused a significant peak in the charcoal profiles seven years after the fire.

The variable depth of the assumed charcoal peaks corresponding to the 1908 fire could be explained by two factors. First, as pointed out by Ohlson *et al.* (2006) the relationship age and depth is highly variable in boreal peat lands according to Clymo *et al.* (1998) and Økland and Ohlson (1998). This variation could even be high within the same peat land (Økland and Ohlson, 1998). The second factor concern the sampling itself. As the core top consists of living *Sphagnum* spp. mosses there is always the question where the real sediment begins. Because of the porous top of living mosses it is almost unavoidably not to compact the top during the transport and handling of the peat core. This could result in a discrepancy between cores.

CONCLUSION

In this study I conclude that the two parameters for charcoal concentration, number of particles (#) and area (mm^2) per unit volume (*e.g.* cm^3), are significantly correlated and that the same pattern from the charcoal profiles will emerge using either parameter. Thus, the extra time put on measure area is not worthwhile unless you are making quantitative studies on charcoal deposition. Further on, using either the charcoal particles > 0.28 mm or > 0.50 mm in diameter, the charcoal profile pattern will be the same. However, because of the low numbers of charcoal particles in the larger size classes and a possible high false positive rate one should be cautious excluding the size class ca. 0.28-0.50 mm. Thus, I conclude that including the 0.28-0.50 mm class in the charcoal analysis is a good compromise between getting reliable data and effort.

Even if a fire has burnt in the vicinity (10-30 m) of the peat core sampled, it might not depose enough charcoal particles to produce a considerable charcoal peak in the charcoal profile. I suggest that fires that have burnt on top of the peat core (fires *in-situ*) might produce a larger amount of charcoal accumulated in the peat profiles compared with fires *ex-situ*.

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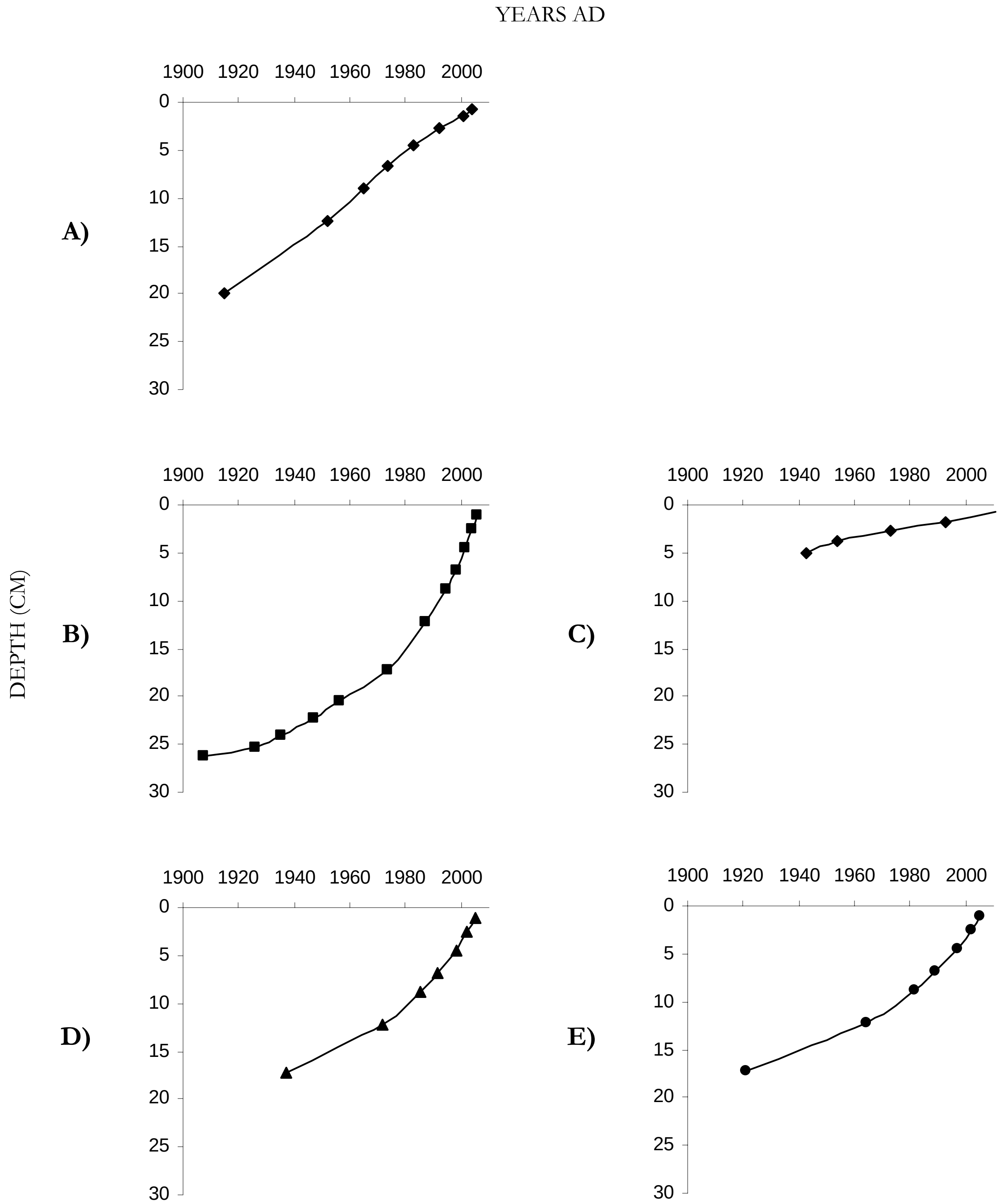
Appendix 1.



^{210}Pb-dating according the CRS model by Flett Res. A) The dating results for C20. B-E considers the dating results according to four different alternatives. B) Normal ^{210}Pb-dating procedure. C) ^{210}Pb-dating at a chosen depth. D) 1st alternative of ^{210}Pb-dating with input of ^{222}Ra. E) 2nd alternative of ^{210}Pb-dating with input of ^{222}Ra.