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Spatial and temporal dynamics of the soil charcoal pool in relation to fire history in a boreal forest landscape

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Abstract: Charcoal pools in boreal forest soils constitute considerable amounts of slow cycling organic matter that is important in the global carbon cycle. However, these pools are characterized by spatio-temporal variations that are not well understood. Here, we have analyzed the charcoal pool in 100 soil samples to determine charcoal stock species origin, and how the size and age of this pool varies across different spatial scales in a Norwegian boreal forest landscape including forests that differ in terms of tree-species composition, tree density and recent fire histories. The size of the charcoal pool was site-specific and highly variable – ranging from 0 to 2108 g m⁻². Geostatistical analyses showed that the charcoal pool was only weakly spatially structured at fine meter scales and between site scales (~100 meter scale). Unexpectedly, there was no significant relationship between the amount of charcoal and contemporary forest composition and density, although there was proportionally more charcoal from broad leaved trees in today's Scots pine forests than in the Norway spruce forests. When relating this information to the fire history, the results indicate that charcoal is lost at a millennial timescale.

Key words: black carbon, charcoal age, charcoal amount, charcoal degradation, forest fire history, pyrogenic carbon

Introduction

Charcoal derived from forest fires is an important part of the pyrogenic and slow cycling fraction of soil organic matter. Due to its importance in the global carbon cycle, pyrogenic black carbon has received much research attention in recent years (Lehmann et al. 2008; Schmidt et al. 2011; Santin et al. 2016). Its functional ecological role has also been acknowledged as fresh charcoal is known to enhance ecosystem productivity (Lehmann et al. 2011). This is also the case in boreal forests (Zackrisson et al. 1996), in which large amounts of charcoal are continuously produced as 5-15 million hectares of boreal forest are consumed by fire annually (Flannigan et al. 2009; Soja et al. 2007). Wildfire production and deposition of macroscopic charcoal is local and highly variable across fine spatial scales (Ohlson and Tryterud 2000). Despite this, spatial and temporal dynamics of this slow cycling soil carbon pool are not fully understood (Schmidt et al. 2011; Santin et al. 2016). For example, some studies show that boreal soil charcoal is truly recalcitrant as it has persisted ever since early Holocene (Couillard et al. 2013; de Lafontaine and Asselin 2011), while other studies indicate that charcoal is lost through various means of degradation since the size of the charcoal pool present in boreal soils is smaller than what could be anticipated on the basis of our knowledge about charcoal production and fire return intervals (Czimczik et al. 2005; Ohlson et al. 2009; Ohlson and Tryterud 2000).

Soil charcoal analysis is a valuable tool in paleoecological research and has for example been used to study disturbance patterns (Gavin 2003), climate change and past tree line positions (Talon 2010), fire regimes and forest- and fire history (Carcaillet 1998; Lertzman et al. 2002; Talon et al. 2005; Touflan et al. 2010). When investigating the dynamics of the soil charcoal pool, the spatial dimension does not pose the greatest challenge, as macroscopic charcoal (longest axis ≥ 0.5 mm) is a reliable and spatially precise proxy for in situ fire (Clark 1988; Ohlson and Tryterud 2000; Patterson et al. 1987; Touflan and Talon 2009; Touflan et al. 2010).

However, it should be mentioned that macroscopic charcoal may be transported over longer distances in large high-intensity fires (Tinner et al. 2006), and secondary transport may occur through overland flow (Scott 2010). Grasping the temporal dimension is more difficult since it often depends on the soil charcoal stock itself, which may be incomplete due to degradation by recurring fires (Kane et al. 2010; Zimmermann et al. 2012, but see Tinkham et al. 2016). Additionally, temporal resolution is further limited through the inbuilt age of the charcoal (Gavin 2001; Ohlson et al. 2009) and radiometric errors (Gavin 2001; Stuiver and Reimer 1993). To support charcoal analysis as a tool to reconstruct past fire activity, information can be derived from stand age- and tree ring analysis, but these cover comparatively short time periods (Gavin et al. 2003a; Kasin et al. 2013). In contrast, lake sediments can provide long-term information, but due to regional source areas, these charcoal records are spatially imprecise (Clark 1988; Higuera et al. 2007). On the other hand, small peat hollows may provide spatially precise long-term information (Higuera et al. 2005; Jacobson Jr and Bradshaw 1981), but these archives are often scarce and characterized by a highly patchy distribution in the forest landscape, and can not be used to reconstruct a picture of past fire activity that is representative on a landscape-scale.

Here we compare the information from charcoal analysis of 100 soil samples with the present forest structure and composition in a Norwegian boreal forest landscape with a known Holocene fire history. The fire history of the sites and major vegetation changes (e.g. the local establishment of Norway spruce (*Picea abies* (L.) Karst.) have been described previously by combining tree-ring- and peat soil analyses (Blanck et al. 2013; Kasin et al. 2013; Storaunet et al. 2013). In these studies, the fire history over the last 600 years has been reconstructed with spatial and temporal accuracy through dendrochronological dating of 736 fire scars. During the last 600 years, periods with longer (about 80 years) or shorter (about 20-40 years) fire return intervals

were determined, but the total number of fires affecting our study sites did not differ significantly among the sites. In a longer Holocene time perspective, charcoal records from four peatlands bordering our present study sites reached back to ca. 9000 calibrated radiocarbon year before present (cal. yr BP), see Kasin et al. (2013). Moreover, these records revealed millennial fire activities at all sites and that these activities were characterized by large temporal variations. The same charcoal records also showed that the local site specific establishment of Norway spruce range from about 520 to 1950 cal. yr BP. Norway spruce invaded Northern Europe in the late Holocene, and is a recent forest dominant in Norway (Giesecke and Bennett 2004; Seppä et al. 2009; Tallantire 1972). In our study, the local establishment of Norway spruce is of great interest as it has been shown to affect fire regimes by reducing local fire frequency and severity (Ohlson et al. 2011). However, all our study sites have been affected by fire after the local spruce establishment (Kasin et al. 2013).

The main aim of this study is to better understand what factors that determine the dynamics of the mineral soil charcoal pool. More precisely, we wanted to know whether the size and spatial variation of the charcoal pool differed among sites and if its species composition and age could be explained by the tree-ring derived fire history and/or the contemporary forest composition.

Material and Methods

Study area

The study area (60°02'N, 09°26'E) has an area of about 1 km² and is situated in the Trillemarka - Rollagsfjell Nature Reserve in the mid-boreal vegetation zone in south east Norway (Moen 1999 and Figure 1). The bedrock is characterized by granites and gneisses of

Precambrian origin, forming north-south extending ridges with deposits of richer moraine material on east-facing slopes. The elevation range from 400 to 650 m a.s.l. with the climate characterized as intermediate oceanic - continental with rather warm summers (July mean 14.7°C) and cold, snow-rich winters (January mean -7.5 °C) (Rollag meteorological station, Norwegian Meteorological Institute (2012)). Norway spruce (*P. abies*) forests dominate the more nutrient rich moraine slopes. The eastern and central areas between the slopes are characterized by mires and nutrient poor Scots pine (*Pinus sylvestris* L.) forests.

Sample sites and procedure for soil sampling

In October 2010 we selected four 2500 m² sites for soil sampling (Figure 1), two in spruce – dominated forests (S1 and S4), and two in pine- dominated forests (S2 and S3). Within each site, we subjectively located five blocks (5 x 10 m) in order to cover the variation in vegetation and topography. Five soil samples were collected at random positions in each block, using a restricted random sampling procedure that is proven to be efficient (Økland 1996; Ohlson et al. 2009) and our sampling procedure yielded a total number of 100 samples (25 at each site). Positions in peat-filled depressions or on naked bedrock were discarded. Soil sampling was conducted using a steel cylinder (50 cm long, inner diameter 5.8 cm), with each sample containing the entire organic layer and a few centimeters of the underlying mineral soil. As a result, sample depth and volume varied with the thickness of the organic layer (2 – 50 cm). The sampling sites were situated on mineral soil in forests adjacent to the mires from which peat samples had been collected earlier, and where the fire history has been described on the basis of the dated charcoal record from the peat samples (Kasin et al. 2013) and dendrochronological analysis of fire scars (Blanck et al. 2013; Storaunet et al. 2013).

The spruce- and pine forests where the soil samples were collected had a vegetation composition typical for the region (plant names follow Lid and Lid (2005)). The forest floor at spruce forest site S1 was covered by the dwarf shrubs *Calluna vulgaris*, *Vaccinium myrtillus*, *V. vitis-idaea* and *Empetrum nigrum* together with feather mosses. *P. sylvestris* and *Betula pubescens* occurred occasionally. At spruce forest site S4, *V. myrtillus* was most abundant among the dwarf shrubs and feather mosses together with *Sphagnum* mosses were common. At the pine forest sites S2 and S3, dwarf shrubs dominated the vegetation on the forest floor, with *C. vulgaris* and *V. myrtillus* being the most frequent species. Feather mosses and lichens occurred in patches in between.

Charcoal analysis and dating

We kept the soil samples deep frozen in plastic bags until analysis in the laboratory. Here, the samples were first oven dried at 80 -105° C (Termaks series TS 8000) and then searched for macroscopic charcoal (longest axis ≥ 0.5 mm) using a magnifying lamp (4x magnification). For each soil sample, the charcoal mass was then determined using an analytical scale (Sartorius ED224S). Our manual hand-picking approach inevitably results in an underestimation of the size of the charcoal pool as micro-charcoal is left out. However, as the microscopic fraction typically make up only minor part of the charcoal pool in Scandinavian boreal forest soils (Ohlson et al. 2009), we are confident that our estimates give a realistic picture of the pool size. Twelve charcoal fragments from sites S2 and S4 were selected for radiocarbon dating according to the following procedure: four fragments were selected from one of the soil samples, and from another two samples from the same block, one fragment each was selected. From another block, we chose two soil samples and then selected one and two charcoal fragments from them,

respectively. From each of the remaining three blocks, a single piece of charcoal was selected. This selection procedure rendered 24 charcoal fragments which were sent to the National Laboratory for ^{14}C dating at the Norwegian University of Science and Technology for preparation, and subsequently AMS radiocarbon dated at the Tandem Laboratory at Uppsala University. Calibrated ages were determined with CALIB (Stuiver and Reimer 1993) (calibrated age ranges at 1 SD). Prior to dating, the tree species from which the charcoal fragment had been derived (hereafter called “parent tree species”) was determined by studying the wood anatomy under a microscope (Schweingruber 1990). Additionally, 153 charcoal fragments were botanically identified, yielding a total number of 177 botanically identified fragments (60 and 59 from the sites with radiocarbon dates (S2 and S4, respectively) and 28 and 30 fragments from the other two sites (S1 and S3, respectively).

Data on geographical position, vegetation, and forest density

We obtained additional information about the sample sites by recording the vegetation composition and determining the basal area of the forest in each block with an angle gauge. We recorded the basal area for the major tree species present (i.e. *P. sylvestris*, *P. abies* and *B. pubescens*) and used it as an indicator of tree density and relative differences in the amounts of fuel. The geographical position of each block was determined in the field with a handheld GPS, and the position of the samples in the blocks was mapped.

Statistics

We used a split-plot ANOVA with site as the main plot-factor and block as the sub-plot factor, to test whether amounts of charcoal (log-transformed) differed significantly between sites.

Visual inspection of the residuals showed that the data met the assumptions of the model. The split-plot ANOVA was followed by a Tukey's test to determine whether contrasts between individual sites was significantly different. These calculations were performed with the R-software for statistical computing (R Development Core Team 2011).

In order to check for spatial structure in the amounts of charcoal we calculated a standardized omnidirectional semivariogram (Rossi et al. 1992) with the help of the R-software and the package geoR, version 1.6-33 (Ribeiro Jr. and Diggle 2001). X and Y coordinates for the samples were found with the help of the GPS coordinates of the sample blocks taken in the field and maps indicating the position of each sample within the block. Prior to calculating the semivariogram, the charcoal mass data were zero-skewness transformed in order to achieve homoscedasticity and ranged on a scale between 0 and 1, see Ohlson et al. (2006) for further details concerning the method used.

Results

Overall, the amount of charcoal in the soil samples averaged 269 ± 40 (± 1 SE) g m^{-2} with a pronounced variation among the individual soil samples. The largest amount, 2108 g m^{-2} , was found in the pine forest at Site 3, and 20 samples (i.e. one fifth of the samples) did not contain any macroscopic charcoal. Figure 2 shows the amounts of macroscopic charcoal in soil samples originating from geographically fixed positions, and our results show that there was no significant spatial structure in the data, although there was a tendency for weak structure in the data over fine scales (meter scale, similar amounts in neighboring samples). This was confirmed by the semivariogram (Figure 3, distance classes between c. 1.5 and 12 m), which also showed weak spatial structure at the between-site scale (c. 200 m). The average amount of macroscopic

charcoal differed significantly among sites ($F=3.95$; $df = 3, 16$; $P=0.027$, split-plot ANOVA) from the spruce forest site S4 with 131 ± 49 to 411 ± 111 g m⁻² at the pine forest site S3 (Table 1). Site S3 and site S4 were the only sites that were significantly different from one another according to the post-hoc Tukey's test ($P = 0.004$). A further indication of the difference between the two forest types was that 34 % of the soil samples from the spruce forests lacked macroscopic charcoal, while this was the case for only 6 % of samples from the pine forests (see Fig. 2). However, the dissimilarity in the size of the charcoal pool was not exclusively driven by forest type as there was no significant difference between spruce site S1 and pine site S2 (Table 1; $P = 0.999$, Tukey's test).

Generally, forest density (i.e. the basal area) was higher in the spruce forest than in the pine forest (S1 and S4, Table I), but there was no clear relationship between the amount of macroscopic charcoal (g m⁻²) in the soil and forest density (Figure 4).

The AMS radiocarbon dates of charcoal fragments from two of the sites (S2 and S4, Table II and Figures 5 and 6) revealed that most of the charcoal particles were younger than about 1100 cal. yr BP (c. 850 cal. yr AD). However, some particles were much older; three dated back to between c. 2300 and 2600 cal. yr BP, and two were about 5000- and 8000 years old, respectively (Table 2). At site S2, more than half of the dated charcoal particles originated from broadleaved species, while more than half of the dated charcoal fragments originated from pine at site S4. However, the majority of the charcoal particles from this site either dated back to the period between c. 300 and 500 cal. yr BP or between c. 900 and 1100 cal. yr BP. This was also the case for the dated charcoal particles from site S2, although their ages were slightly more variable as compared to those from site S4 (Table 2). Several of the dated charcoal particles,

especially from site S2, originated from the time period covered by the dendrochronological analysis of the fire history in the area (i.e. AD 1335 to present, see Storaunet et al. 2013).

Many of the dated charcoal particles originated from fires occurring after the establishment of spruce in the area, see Kasin et al. (2013), i.e. nine out of twelve particles at site S2, and four out of twelve at site S4 (Table 2). Intriguingly, spruce charcoal pre-dated the approximate timing of spruce establishment by about 400 years as determined by pollen analysis in Kasin et al. (2013). That there were multiple and even aged charcoal particles from single soil samples indicates that a number of particles, and perhaps the majority were likely to have been produced by the same fire events (or a few events that were adjacent in time), see Table 2.

At all sites the majority of charcoal fragments originated from Scots pine, with the proportion of pine charcoal particles reaching a maximum value (c. 70 – 80%) in present-day spruce forest sites (Fig. 5). Only two out of the 177 charcoal particles that were identified to species originated from spruce, and they were both selected from one soil sample from present-day spruce forest location S4. According to their similar radiocarbon dates (Table 2) they may even have originated from the same tree. Moreover, there was more charcoal from broad leaved species in the soil samples from today's pine forest sites, with charcoal originating from *Sorbus aucuparia* being exclusive for this forest type. In this context, the occurrence of broad-leaf charcoal may indicate a prevalence of surface fires in the contemporary pine forests.

To summarize our results, Fig. 6 shows the size, age and composition of the charcoal pool, including its spatial and temporal variation in the mineral soil samples.

Discussion

Charcoal amount and production rates

The average charcoal mass of 131 to 411 g m⁻² at the four sites is within the range of what others have found in their studies of Scandinavian boreal forest sites (Ohlson et al. 2009; Ohlson et al. 2013). In the latter study, conducted 100 km away from our study area, it was found that there was a positive relationship between basal area of present-day forest stands and the amount of charcoal in the soil, supporting findings that forest density and hence the amount of biomass present at a given site is an important factor determining the amount of charcoal that can be produced locally (Carcaillet and Talon 2001). However, in our present study we did not find such a relationship. In fact, the opposite was the case with the soil charcoal pool being smallest at spruce forest site S4 (Table 1), where the basal area was the largest among the four sites. This indicates that other site-specific processes that have occurred in rather recent time may have weakened the relationship between the size of the soil charcoal pool and the structure and composition of today's forests. Examples of such processes are human land use in the form of logging and use of fire to improve grazing qualities in the forests (see Storaunet et al. 2013; Blanck et al. 2013). This lack of correlation could also be found for the peat soil charcoal pool in the present forest landscape, which has been described in detail by Kasin et al. (2013). Moreover, Kasin et al. (2013) found that there was no relationship between the amounts of charcoal in the peat and in the bordering mineral soil, emphasizing that properties linked to specific biotopes (e.g. hydrology and vegetation cover) contribute to variation in charcoal amounts at spatial scales over a few tens of meters. This high degree of spatial variation in the size of the charcoal pool is not only driven by the difference between peat and mineral soils as there was also considerable spatial variation within the same soil type, i.e. the mineral soil in this study (Table 1 and Figure 2). Here, factors such as translocation after primary deposition, e.g. through surface processes

(Scott and Damblon 2010), soil mixing (Gavin 2003), or variation in fuel amounts (Ohlson et al. 2013), affect the spatial and temporal dynamics of the charcoal pool.

Our geostatistical analysis revealed that the size of the charcoal pool was weakly spatially structured at fine spatial scales (1 to 12 m), but the fact that the size of the charcoal pool differed significantly among sites (i.e. between sites S3 and S4) indicates that the pool was also spatially structured at the broader between-site scale. That the soil charcoal pool is spatially structured across fine spatial scales is corroborated by (Gavin et al. 2003b) and Touflan and Talon (2009) in their studies from Canada and the French Southern Alps, respectively. Interestingly, despite variation in charcoal amounts among sites, the proportions of the different tree species from which the charcoal was derived showed little variation (see Table 2), suggesting that past forests had rather similar tree species compositions. High amounts of the same charcoal species across fine spatial scales may also be explained by the possibility of hitting the same burned log multiple times, or small scale topography variation (e.g. in depressions, on the foot of slopes), leading to the gathering of charcoal particles with a common origin.

Spruce establishment

The establishment of spruce has been shown to alter the fire regime and cause a decline in fire frequency, or even cessation of fire occurrence in subdued topographic settings (Ohlson et al. 2011; Tryterud 2003). Consequently, the production of new charcoal from spruce should be limited. Our results show that this was the case as spruce charcoal was only found in a single sample from spruce forest site S4. An explanation for the general scarcity of spruce charcoal may be that the stand scale history of spruce has been too short in order to provide a measurable effect on the soil charcoal. As a major part of the soil charcoal pool at spruce forest sites was

comprised of charcoal derived from Scots pine, it would be natural to presume that most of this charcoal should originate from the time before spruce establishment. However, this can not be the case due to the generally young charcoal particles (this study) and the fire history of the forest landscape, as documented by Storaunet et al. (2013) and Kasin et al. (2013). According to dendrochronological analysis of fire scars by Storaunet et al. (2013) and Blanck et al. (2013), the study sites have been affected by several fire events during the last 500 years, when spruce were present in the area (Kasin et al. 2013). However, these two studies suggest that the majority of these fires were local low-intensity fires that were small in size, and probably caused by human land use (Blanck et al. 2013), thus producing only minor amounts of charcoal. A further explanation for the general lack of charcoal from spruce can be that resinous pine wood may preserve longer after charring than does softer spruce wood. Here, it should though be noted that there is a complex relationship between the presence of Norway spruce and fire activity (Bradshaw et al. 2010), which is corroborated by Brown and Giesecke (2014), who found high occasional charcoal deposition rates after the local establishment of spruce in central Sweden, which reflect large and/or severe burns in the forest landscapes. However, Brown and Giesecke (2014) analyzed lake sedimentary charcoal records that are not spatially precise as they collect charcoal that has been transported from terrestrial fire source areas (see e.g. Higuera et al. 2007; Ohlson et al. 2013), and it is thus not possible to conclude that fire has been locally and *in situ* present in forests dominated by spruce.

Charcoal age and degradation rates

It is well known that charcoal degradation rates are dependent on the properties of the charcoal itself, environmental factors and recurring fires (Baldock and Smernik 2002; Gundale

and DeLuca 2006; Kasin and Ohlson 2013; Preston and Schmidt 2006; Santin et al. 2013; Tinkham 2016). Due to radiometric- and inbuilt-age errors (Gavin 2001; Stuiver and Reimer 1993), the exact date for a fire event in which wood charcoal was formed cannot be determined by radiocarbon dating of charcoal. The inbuilt age error can be substantial in some ecosystems, i.e. several hundred years (Gavin 2001), but we believe it to be much smaller in the case of some of our samples, see de Lafontaine and Payette (2012). The main reason for this is that many of the dated particles originated from broad leaved tree species that are short lived and that litter from these species decay relatively rapid. Even if the inbuilt age error may have been larger in some of our dated particles, many of the fire events, in which they were produced, could still correspond to fires documented by the dendrochronological analysis in Storaunet et al. (2013). Interestingly, charcoal from this time-period was nearly absent from the mires adjacent to the soil sample sites (Kasin et al. 2013), supporting the assumption that the majority of the charcoal produced during the last centuries was left behind by a fine-scale mosaic of low intensity fires. Intriguingly, one of the dated charcoal particles from site S2 was even younger than the latest fire dated through the tree-ring analysis (Table 2, TRa – 3638, Younger than AD 1890).

Presupposing that our charcoal dates are representative for the mineral soil charcoal pool in our study landscape, this pool must be dominated by charcoal that is younger than about 1200 years (see Table 2). However, fires have occurred at these sites throughout millennia (Kasin et al. 2013). For example, charcoal records from the peatland adjacent to site S2 reveal abundant occurrences of charcoal in the peat layers originating from the time-period between c. 3000 to 6000 cal. yr BP. If mineral soil charcoal was not decomposed, or lost in recurrent fires, charcoal from these older fires ought to be more abundant in our mineral soil samples. Consequently, our data contradicts de Lafontaine and Asselin (2011), who proposed that macroscopic soil charcoal

particles are generally stable over millennia and should thus not be lost through degradation. Numerous recent studies have focused on charcoal degradation rates, but to the best of our knowledge, only few studies have estimated charcoal consumption by recurring fires, i.e. Santin et al. (2013) and Tinkham et al. (2016). Interestingly, even though recurring fires may have the potential to consume a major part of the pyrogenic soil charcoal, these two studies show that only a minor part is consumed during recurring fire events, which in turn implies that parts of the charcoal pool undergo rapid re-mineralization and degradation (see e.g. Ascough et al. 2011; Kasin and Ohlson 2013; Singh et al. 2012; Zimmermann et al. 2012). Our present data corroborate rapid degradation, and thus provide support for Ohlson and Tryterud (2000), Czimczik et al. (2005) and Ohlson et al. (2009), who have indicated that the pyrogenic carbon pool in boreal forest soils is both younger and smaller in size than what could be anticipated if the soil charcoal should be truly recalcitrant. However, charcoal and other forms of pyrogenic carbon are chemically and physically highly heterogenic (Schmidt and Noack 2000; Rumpel et al. 2011), and incompletely pyrolysed materials are more readily decomposed than materials that are completely pyrolysed (Knicker 2011; Naisse et al. 2013; Wieder et al. 2013). This means that a large proportion of for example incompletely pyrolysed charcoal may be lost in short time after a fire, while some proportions are very recalcitrant and can survive over several millennia due to complete pyrolysis and permineralization, i.e. a concealment of the anatomical wood structures by mineral infilling inside the cavities (see de Lafontaine et al. 2011). In this context, it should also be mentioned that it is likely our focus on large macroscopic charcoal has contributed to an underestimation of the age of the charcoal pool because charcoal particle size will inevitably decline over time by erosion and other physical and biological processes (e.g. Czimczik and Masiello 2007; Preston and Schmidt 2009; Rumpel et al. 2006). Moreover, given that we had

357 used a chemical method instead of our hand-picking to quantify the size of the charcoal pool, it is
358 very probable that our results would have been somewhat different as it is well documented that
359 different pyrogenic carbon quantification methods deliver different results (Hammes et al. 2007;
360 Quénéa et al. 2006; Schmidt and Noack 2000).

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Conclusions

Even though the size of the charcoal pool was highly variable with a range from 0 to 2108 g m⁻², it was only weakly spatially structured at two different scales, i.e. a fine meter scale, and at a between-site 100 m scale. Data obtained by botanical identification and dating of charcoal particles suggest that fine scale variation may arise from patterns in the pre-fire charcoal stock, e.g. positions of trees and logs on the ground, while the large scale variations is likely to originate from idiosyncratic differences among sites. There was no correlation between the size and the composition of the charcoal pool and today's forests composition and density. This is likely due to recent human land use, such as logging and use of fire, which have determined today's forest structure and composition. A comparison of the age distribution of the macroscopic charcoal pool with the local dendrochronologically determined fire history indicates that this charcoal size fraction is lost from the soil charcoal pool at a millennial time scale.

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Table 1. Amount of macroscopic charcoal and forest density. Figure 1 gives information about site locations in the Trillemarka-Rollagsfjell Nature reserve, SE Norway.

Site and contemporary forest type	Average amount of macroscopic charcoal	Median	Min. charcoal (g m ⁻²)	Max. charcoal (g m ⁻²)	Average basal area (m ² ha ⁻¹)
S1 spruce	329 (85)	239	0	1533	15 (2)
S2 pine	204 (53)	106	0	797	10 (0.4)
S3 pine	411 (111)	212	7	2108	10 (2)
S4 spruce	131 (49)	13	0	823	19 (3)
Spruce	230 (51)	29			
Pine	308 (63)	152			
All sites	269 (40)	97			

Note: Standard errors are provided in parentheses.

Table 2. AMS radiocarbon dates and botanical origin of macroscopic charcoal from pine forest site S2 and spruce forest site S4 in the Trillemarka-Rollagsfjell Nature reserve, SE Norway.

Calibrated age determined with CALIB according to Stuiver and Reimer (1993). Calibrated age ranges at 1 standard deviation (SD).

Lab. ref.	Site	Charcoal parent tree species	Calibrated age
TRa-3637	S2	<i>Betula sp.</i>	AD 1040-1165
TRa-3638	S2	<i>Pinus sylvestris</i>	Y. than AD1890
TRa-3633	S2	<i>Betula sp.</i>	BC 765-515
TRa-3634	S2	<i>Pinus sylvestris</i> or <i>Picea abies</i>	AD 1300-1395
TRa-3635	S2	<i>Sorbus aucuparia</i>	BC 385-205
TRa-3636	S2	<i>Sorbus aucuparia</i>	AD 1305-1400
TRa-3642	S2	<i>Betula sp.</i>	AD 1485-1635
TRa-3643	S2	<i>Betula sp.</i>	AD 1000-1025
TRa-3640	S2	<i>Pinus sylvestris</i>	AD 1430-1445
TRa-3641	S2	<i>Pinus sylvestris</i>	AD 1435-1450
TRa-3639	S2	<i>Pinus sylvestris</i> or <i>Picea abies</i>	BC 2905-2785
TRa-3644	S2	<i>Betula sp.</i>	AD 1185-1240
TRa-3647	S4	<i>Pinus sylvestris</i> or <i>Picea abies</i>	AD 1490-1640
TRa-3648	S4	<i>Pinus sylvestris</i>	AD 815-890
TRa-3649	S4	<i>Pinus sylvestris</i>	AD 785-890
TRa-3650	S4	<i>Pinus sylvestris</i>	AD 885-970
TRa-3645	S4	<i>Pinus sylvestris</i> or <i>Picea abies</i>	BC 5690 -5590
TRa-3646	S4	<i>Betula sp.</i>	AD 1475-1630
TRa-3656	S4	<i>Pinus sylvestris</i>	Y. than AD 1660
TRa-3652	S4	<i>Picea abies</i>	AD 1015-1035
TRa-3653	S4	<i>Picea abies</i>	AD 965-1010
TRa-3654	S4	<i>Pinus sylvestris</i>	BC 770-530
TRa-3651	S4	<i>Pinus sylvestris</i>	AD 780-885
TRa-3655	S4	<i>Pinus sylvestris</i>	AD 1445-1485

Figure captions – Kasin et al.

Fig. 1. The study area in SE Norway (insert top-left) and locations for soil sampling at four sites in the Trillemarka-Rollagsfjell Nature reserve.

Fig. 2. Bubble plot showing the spatial distribution of charcoal mass in soil samples collected from four different 50 x 50 m² forest sites in the Trillemarka-Rollagsfjell Nature reserve, SE Norway. Sites 1 and 4 are spruce forests, and Sites 2 and 3 are pine forests. Note the logarithmic scale of Samples containing charcoal are marked with dots and samples without charcoal are marked with squares. See Fig. 1 for site locations in the forest landscape.

Fig. 3. Standardized semivariogram for amount of macroscopic charcoal in forest soil samples (all samples from all four sites, $n = 100$ – see Fig. 1). A variable is spatially structured in distance intervals where the semivariogram values increase with increasing distance, i.e. between c. 1.5 – 12 and 24 – 200 m, respectively. However, the spatial structure in our data is weak as the semivariogram values fall within the dotted line envelope obtained by 999 permutations. Labels on the horizontal axis indicate midpoints of distance lag classes, expressed as 2ⁿ m. Auxiliary distance classes, expressed in m, are also added to the horizontal axis (in parenthesis), and the horizontal line on the value of 1 show the semivariance on a standardized scale that is common for the both the semivariance and the measured variable.

Fig. 4. Relationship between forest density and soil charcoal amount per block, which represents the average amount of charcoal from five soil samples at each site.

Fig. 5. Proportion of charcoal parent tree species in soil samples from spruce and pine forests at four different sites in the Trillemarka-Rollagsfjell Nature reserve, SE Norway. “Spruce” and “Pine” below the site number indicate the present-day forest type. Note that the number of charcoal particles, from which the proportions were calculated, differ among sites, i.e. S1: $n=28$, S2: $n=60$, S3: $n=30$, S4: $n=59$.

Fig. 6. Schematic drawing illustrating how spatial and temporal variations in the soil charcoal pool determine the composition of charcoal in contemporary soil samples. A and B: cylindrical soil samples. The squares depict four “time windows” showing the forest floor after forest fires from the past. Occurrence of macroscopic charcoal is indicated by different lines: solid lines = charcoal still present at the time of sampling; dashed lines = charcoal originally produced at a given location, but which has been lost in later fires, or through other degradation pathways. Note that the probability that locally produced charcoal has gone lost, increases over time.

Fig. 1. Kasin et al.

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