# Spatial variation of surface soil carbon in a boreal forest – the role of historical fires, contemporary vegetation, and hydro-topography

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## Abstract

Knowledge about the spatial variation of boreal forest soil carbon (C) stocks is limited, but crucial for establishing management practices that prevent losses of soil C. Here, we quantified the surface soil C stocks across small spatial scales, and aim to contribute to an improved understanding of the drivers involved in boreal forest soil C accumulation. Our study is based on C analyses of 192 soil cores, positioned and recorded systematically within a forest area of 11 ha. The study area is a south-central Norwegian boreal forest landscape, where the fire history for the past 650 years has been reconstructed. Soil C stocks ranged from 1.3 to 96.7 kg $m^{-2}$ and were related to fire frequency, ecosystem productivity, vegetation attributes, and hydro-topography. Soil C stocks increased with soil nitrogen concentration, soil water content, *Sphagnum*- and litter-dominated forest floor vegetation, and proportion of silt in the mineral soil, and decreased with fire frequency in site 1, feathermoss- and lichen-dominated forest floor vegetation and increasing slope. Our results emphasize that boreal forest surface soil C stocks are highly variable in size across fine spatial scales, shaped by an interplay between historical forest fires, ecosystem productivity, forest floor vegetation, and hydro-topography.

Key words: Organic surface carbon stocks, forest fire history, hydro-topography, spatial fine-scale variation

## 1. Introduction

Boreal forest soils store approximately 20% of the terrestrial carbon (C) stock (Scharlemann et al., 2014), and thus play an important role in the global C dynamics (Pan et al., 2011). The large build-up of C in boreal forest soils are mainly due to low temperatures that lead to low decomposition rates (Malhi et al., 1999; DeLuca & Boisvenue, 2012). Even so, these stocks can be highly variable on fine spatial scales (Kristensen et al. 2015), which imply that additional drivers are involved. Specifically, boreal forest soil C stocks are controlled by: I) Temperature and humidity which drives primary production, decomposition and respiration (Jobbágy & Jackson, 2000; Pan et al., 2011); II) Fire regimes which impact the soil structure, nutrient pools and biochemistry (Andrieux et al., 2018; McLauchlan et al., 2020; Palviainen et al., 2020; Mack et al., 2021); III) Climate- and fire interactions, which alter boreal forest vegetation composition and hence litter quality, root distribution, and above-belowground allocation patterns (Zackrisson et al., 1996; Jobbágy & Jackson, 2000; Nilsson & Wardle, 2005); and IV) Soil texture and topography that determine hydrological conditions and build-up of organic matter, where coarse-texture soils favour faster organic matter decomposition (Harden et al., 1997; Harden et al., 2000; Olsson et al., 2009; Zajícová & Chuman, 2020).

Forest ecosystems are experiencing alterations in fire regimes as climate is changing (Flannigan et al., 2000; Whitlock et al., 2003; Seidl et al., 2020). This will impact the boreal forest soil C stocks significantly as the proportion of fire-consumed C is determined by both fire intensity and frequency (Williams et al., 2016). Typically, higher fire intensities and increased frequencies result in larger C losses and longer soil C stock recovery times (Alcaniz et al., 2018; Pellegrini et al., 2018), which both have been found to be variable in boreal forests (Hume et al., 2016; Palviainen et al., 2020; Li et al., 2021). Yet, a general trend in the boreal forest C stock recovery process is that an initial period with fast accumulation of organic matter is followed by slow and continuous increases of the soil C stocks. This can go on for several hundreds, or even thousands of years, related to vegetation attributes of the forest ecosystem (Wardle et al., 2012; Andrieux et al., 2018; Mack et al., 2021). However, despite a growing body of research on how fire impacts soil C stocks in boreal forests, we lack information about relationships between occurrences of historical fires and contemporary soil C stock sizes, as both figures are known to be spatially variable in boreal forests (Zackrisson, 1977; Niklasson & Granström, 2000; Pellegrini et al., 2018; McLauchlan et al., 2020).

Here we focus on the interplay between contemporary and historical drivers of forest organic surface soil C stock sizes (hereafter termed soil C). Our main aim is to increase the understanding of processes involved in forest soil C dynamics and improve the knowledge about size variation over fine spatial scales. To do this, we utilized a detailed dendrochronology-based study of fire history (Storaunet et al., 2013) to establish a study design that allow us to investigate if and how the size of boreal forest soil C stocks varies across different historical fire regimes. We used this set up to address the following questions. (I) To which extent does historical high-resolution fire data (i.e., time since last fire and fire frequency) relate to present soil C stock sizes? (II) Does hydro-topography and contemporary vegetation attributes play a more important role than fire history in shaping the spatial variation in soil C stock sizes? We focused on the organic surface soil C layer since it is strongly affected by forest fires (Li et al., 2021; Hanes et al., 2022), and a key determinant of the C dynamics in the boreal forest soil (Högberg et al., 2001; Lindahl et al., 2007).

## 2. Materials and methods

### 2.1 *Study sites*

The study area consisted of two forest sites located in Trillemarka-Rollagsfjell Nature Reserve in south-central Norway (60°2′N, 9°25′E). With an area of 147 $km^2$, Trillemarka-Rollagsfjell Nature Reserve is one of the largest forested areas in south-central Norway with little influence of modern clearcutting practices. It belongs to the mid-boreal vegetation zone, with an intermediate oceanic and continental climate, experiencing mean annual precipitation of 800-900 mm and mean annual temperature of 5°C, with monthly means varying from -5.6°C in January to 16.3°C in July. Climate data are averages from Veggli, located 15 km W of the study area, 275 m a.s.l., and Sigdal – Nedre Eggedal, located 11 km NNE from the study area, 143 m a.s.l. (https://seklima.met.no/observations/). The topography is characterized by north-south ridges of Precambrian rocks that constitute a bedrock of acid granites and gneisses, as well as east-facing slopes of rich moraine material.

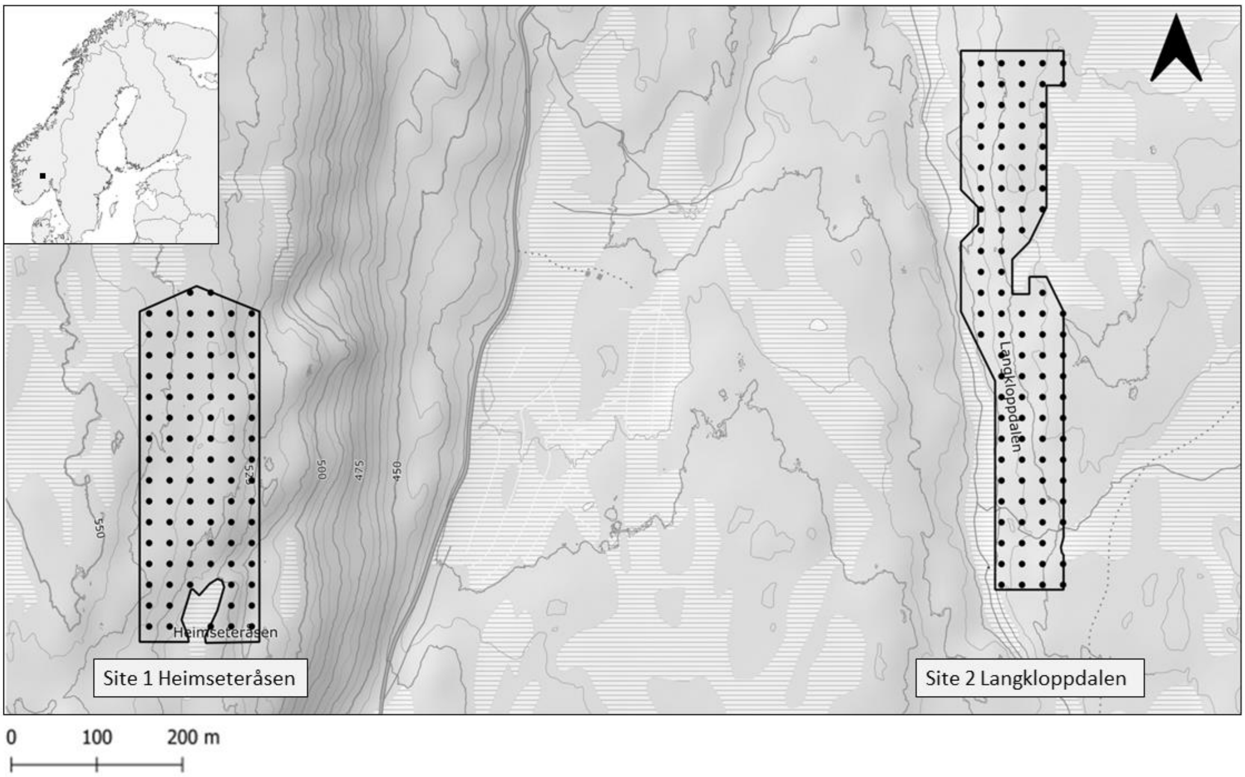


**Fig. 1** Location of the two study sites (site 1 and site 2) and positions of plots for soil sampling and vegetation analyses in Trillemarka-Rollagsfjell Nature Reserve, south-central Norway. Topographic contour line distance=5 m. Data retrieved from The Norwegian Mapping Authority (2017).

Two approximately 5.5 ha study sites were selected within a 360-ha area of the Nature Reserve at elevations ranging from 400 (site 2, Langkloppdalen) to 550 m a.s.l. (site 1, Heimseteråsen) (Fig. 1). The forests were nutrient-poor and dominated by Scots pine (*Pinus sylvestris*), with sparse occurrences of Norway spruce (*Picea abies*), downy birch (*Betula pubescens*), and rowan (*Sorbus aucuparia*). The two study sites were placed in order to represent a broad range of differences in time since last fire and fire frequency (Fig. 2) as outlined in Storaunet et al. (2013) (see below / Section 2.2.2), while avoiding open unforested peatland areas.

### 2.2 Data collection

#### 2.2.1 Organic surface soil sampling

In September-October 2020 we collected a total of 195 soil samples at plots that were located systematically 24 m apart across both sites (Fig. 1). At each soil sample plot, we sampled the entire organic surface soil horizon including a few centimetres of the underlaying mineral layer with a sharp-edged cylindric soil corer (ø 58 mm). The soil samples were divided in the field into organic layer and mineral layer and stored in separate sealed plastic bags. We used soil depth and corer inner area to calculate sample volume. Hence, soil sample depth and volume varied with thickness of the organic surface soil. We relocated plots on bare bedrock (*n*=8, starting one meter north and moving 90 degrees clockwise until a suitable location was achieved) and used a metal rod to measure the thickness of the organic surface soil in a few plots (*n*=18), where the depth of the organic soil exceeded the length of the soil corer (40 cm). Thus, our estimates cover organic soil depths ranging from 2 to 110 cm, averaging 21.3±1.6 cm (±SE). All soil samples were brought back to the lab, weighed, and dried at 40°C until mass was constant. Prior to further analyses, the dry soil was weighed, and the organic soil homogenized by a rotary mill (Brabender Rotary Mill, Germany).

#### 2.2.2 Fire history

The fire history data originated from Storaunet et al. (2013), who delineated 57 individual forest fires in the landscape over the past 650 years by their high-resolution sampling and cross-dating of fire scars. A strong anthropogenic signal was found in the fire regime from 1600 and onwards, with an increased fire frequency during 16-1700s and an almost cessation of fires after 1800. From these fire historical data, we extracted the variables “Time since last fire” and “Fire frequency” for each soil sample plot across our study sites (Fig. 2) (see Storaunet et al. 2013 for methodological details).

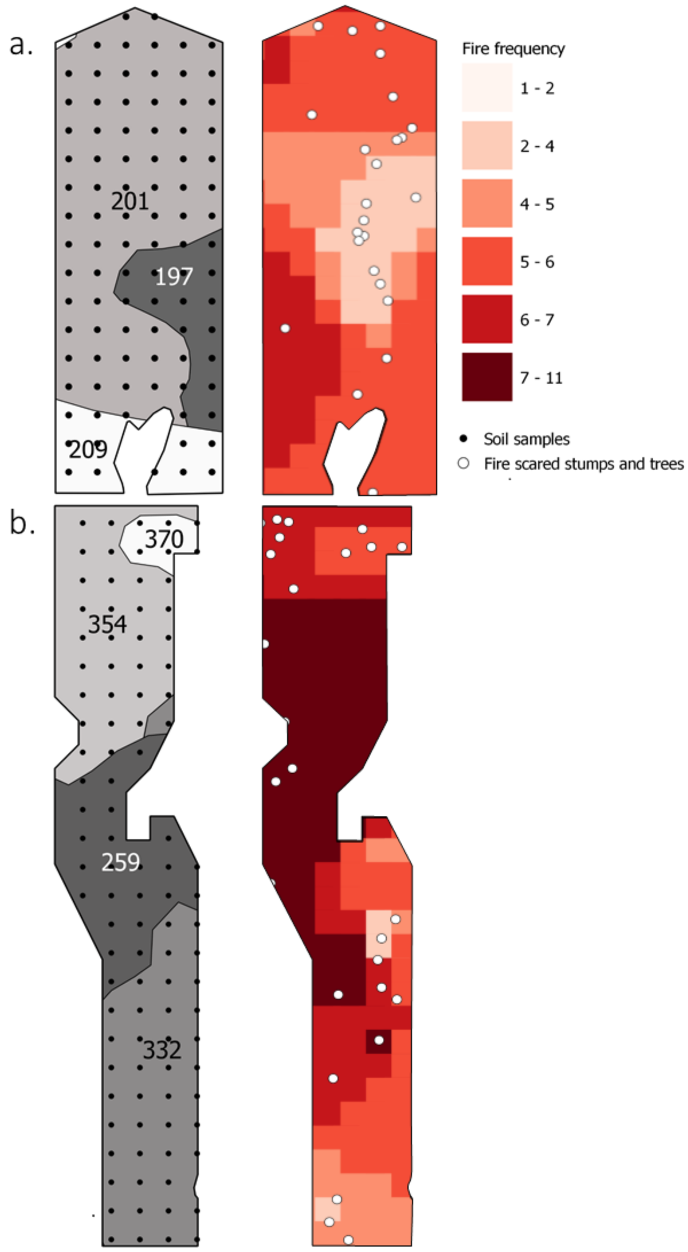


**Fig. 2** Fire history characteristics of the study sites 1 and 2 (a. and b.). Numbers in left panels denote number of years since the last fire. Right panels depict number of recurring fires since AD 1350. Data extracted from Storaunet et al. (2013). Black dots in left panels denote soil sample locations, whereas white dots in right panels denote fire scarred wooden samples.

### *2.2.3 Vegetation*

Quadrat vegetation sampling plots of 50x50 cm were located around the center of all soil sampling positions. We recorded percentage forest floor vegetation cover according to these vegetation categories: *Sphagnum* mosses; feather mosses (mainly *Pleurozium schreberi* and *Hylocomium splendens*); lichens (mostly *Cladonia* species and *Cetraria islandica*); litter (field layer vegetation, but no forest floor vegetation); naked (bare ground without any vegetation), plots on bare bedrock were relocated in the sampling procedure (*n*=8). In addition, we estimated the forest stand basal area of *P. sylvestris*, *P. abies* and deciduous trees using a relascope (factor 1) at every soil sample plot.

### 2.2.4 Topography and wetness

We defined microtopography of the 50x50 cm sample plot as convex (i.e., well drained hills), concave (i.e., terrain depressions), or flat, and registered aspect and slope using a compass and a clinometer (referred to as 'plot' in analyses). We also derived topography for the soil sampling plots from a 0.25x0.25 m resolution digital terrain model (DTM) (The Norwegian Mapping Authority, 2017). We retrieved elevation, slope and aspect using QGIS 3.16.7 (QGIS.org, 2022), and averaged slope and aspect over a 24x24 m area around each sample plot (referred to as 'terrain' in analyses). Further, we defined soil water content as sample dry weight divided by sample wet weight, subtracted from one. As rainfall conditions varied prior to sampling, the soil wetness variable was centred and scaled by subtracting the mean and dividing by the SD per sampling date.

## 2.3 Soil analyses

Total C and nitrogen (N) concentrations (%) of the organic surface soil were determined by automated dry combustion in an elemental analyser (vario MICRO cube, Elementar, Germany). The dry matter mass was used to determine bulk density (BD; g $cm^{-3}$) of the organic and mineral soil fraction. C and N stocks (kg $m^{-2}$) in the soil were thereafter calculated by multiplying C (%) or N (%) with BD (g $cm^{-3}$) and soil depth (cm) and scaled to kg $m^{-2}$. Soil texture of 21 mineral soil samples were determined. The 21 samples were chosen based on a stratified random procedure where samples first were grouped by soil C stock size (i.e., largest, median, and smallest). For each category, we included the 14 top-ranked samples from which we randomly drew 7 samples. Samples without mineral soil were excluded. The selected samples were carefully sieved through a 2 mm sieve before they were analysed by a laser diffraction particle size analyzer (Beckman Coulter LS 13 320, United States).

## 2.4 Data analyses

Prior to statistical analyses, data were explored visually by boxplots, dotplots, and pairplots to identify patterns in the data, potential outliers, and covariation. We identified three outliers using a Bonferroni outlier test. These samples had unrealistically low C% values due to contamination with mineral soil, and were thus removed, reducing the sample size to 192. A principal component analysis (PCA) was performed on the 5 forest floor vegetation categories outlined above (Appendix A, Fig. A.1). We did this to identify forest floor vegetation gradients with contrasting properties. We give an overview of all response- and predictor variables in Appendix A, Table A.1.

To test the effects of predictor variables, we used linear mixed effect models. The two sites were included as random effects to deal with potential site-specific difference introduced by the study design. However, site was not significant in explaining overall soil C stock variation. As we selected the study sites to cover a range of differences in fire history, interaction terms between site and fire frequency as well as site and time since last fire were included in the models. The model assumptions of normality and homoscedasticity of residuals were visually inspected. As the normality assumption was violated, we applied a $\log_e$-transformation of soil C stocks to improve the fit of the data.

We used information-theoretic model averaging based on Akaike information criterion (AIC) to assess the relative importance of each predictor variable in relation to soil C stocks (Burnham & Anderson, 2002). Strongly correlated variables ($|r| \geq 0.5$) were not allowed in the same model (see Appendix A Fig. A.2 for covariation plot). We calculated variable importance score of each predictor variable by summing the Akaike weights over all models including the relevant term. Corresponding estimated coefficients were averaged over the same models and weighted according to the probability of each model. Soil texture (i.e., sand, silt, and clay) in relation to soil C stocks were modelled in separate mixed effect models due to small sample size ($n$=21). We did all statistical analyses in R version 4.1.1 (RStudio Team, 2020), using the packages 'vegan', 'emmeans', 'nlme' and 'MuMIN'. All maps were created using QGIS 3.16.7 (QGIS.org, 2022).

## 3. Results

C stocks in the organic layer ranged from 1.3 kg $m^{-2}$ to 96.7 kg $m^{-2}$ across the study sites and averaged 9.1±0.9 kg $m^{-2}$. The relative importance of the different drivers of C soil stocks are given in Fig. 3a, and the predictor variables included in the best model explained half of the variation in soil C stocks (marginal $R^2$=0.51, see Appendix B, Table. B.1 for all models with $\Delta$AIC $< 2$). N-rich organic surface soil had larger C stocks (Fig. 3b, Fig. 4a). Further, soil C varied with vegetation attributes. Plots with a larger proportion of litter compared to lichen (forest floor vegetation PC2) and peatmoss compared to feathermoss (forest floor vegetation PC1) had larger soil C stocks (Fig. 3b, Fig. 4b, d, see Appendix A Fig. A.1 for PCA plot). Fine-scale spatial variation in hydro-topography (i.e., soil water content and slope) also influenced the soil C stocks. Wetter areas had larger soil C stocks compared to drier, and soil C stocks decreased with increasing slope (Fig. 3b, Fig. 4c, e). Lastly, a significant interaction term between fire frequency and site implied that soil C decreased with increasing fire frequency at site 1: areas with a low fire frequency (i.e., 3-4 fires) during the past 650 years had larger soil C stocks compared to areas with a high fire frequency (i.e., 6-7 fires). There was no effect of fire frequency at site 2 (Fig. 4f). In addition, areas with a higher proportion of silt in the mineral soil had larger soil C stocks (separate mixed effect model estimate: 0.16, CI: 0.02-0.31, *n*=21). Proportion of silt in the mineral soil varied from 13% to 61% across our study sites and was highly correlated with sand content (r=-0.99).

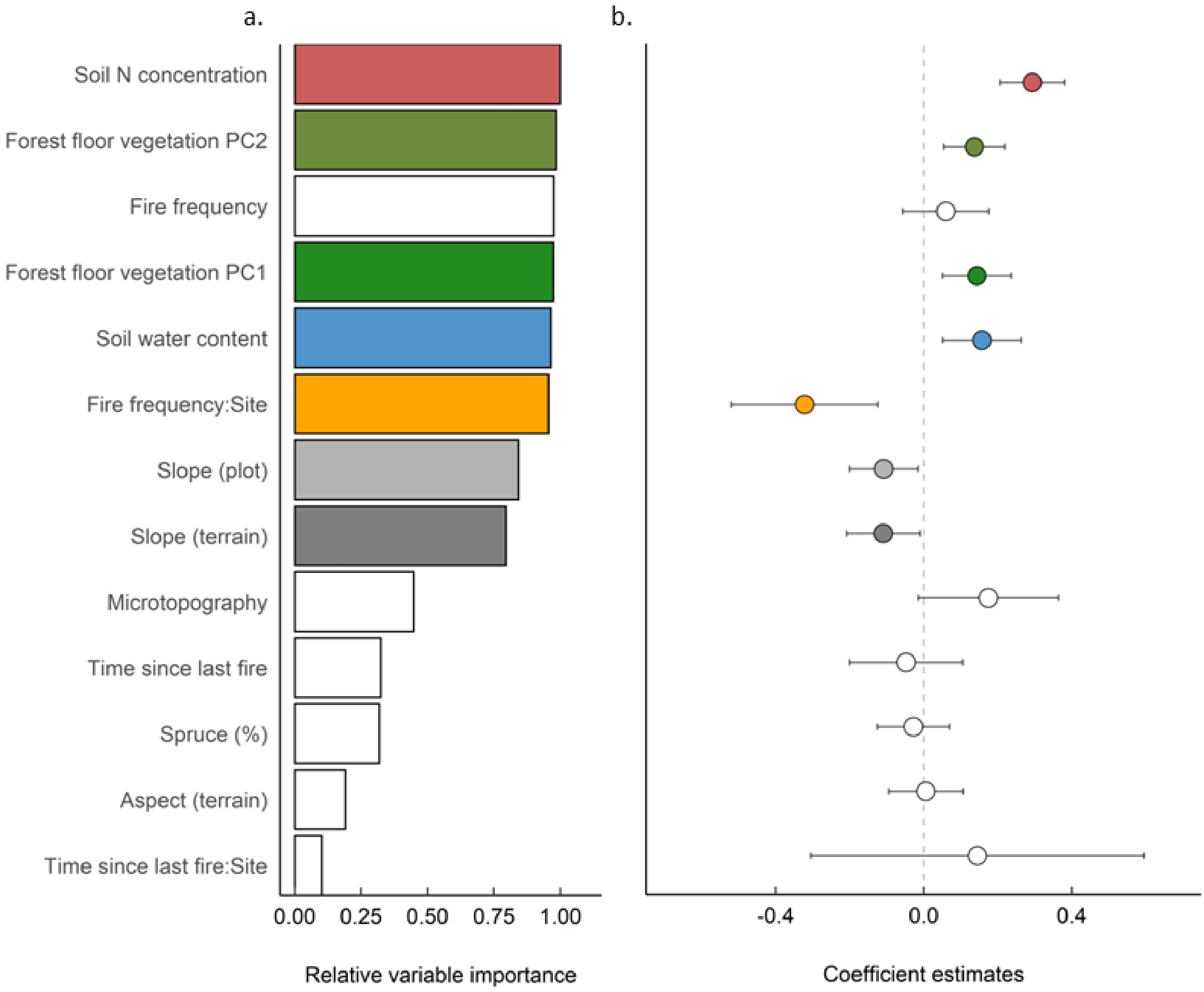


**Fig. 3** (a) Relative variable importance scores, and (b) corresponding significant coefficient estimates from model average analysis of predictors of boreal forest soil C stocks. The variable importance scores can be interpreted as the probability of that variable being a part of the best model and can therefore be used to rank the predictors in order of importance. Model average coefficients were averaged across all models and means, 95% CI are shown where CI's crossing zero are non-significant. All continuous predictor variables are centered and scaled to be directly comparable. Forest floor vegetation PC1 is a vegetation gradient going from feathermoss- to peatmoss-dominated sampling plots, and forest floor vegetation PC2 a vegetation gradient going from lichen- to litter-dominated sampling plots. Interacting terms between site and fire history have site 1 as reference level.

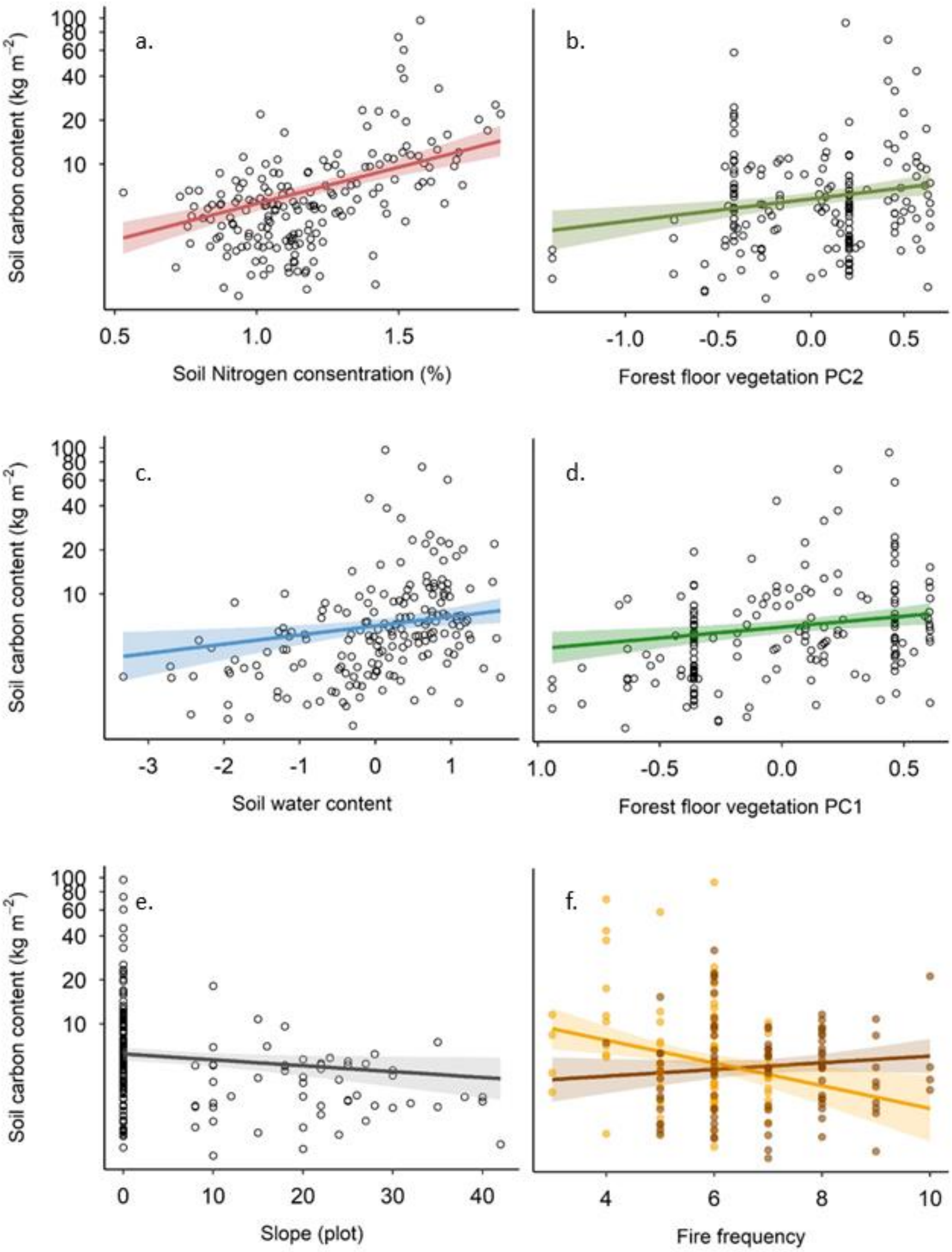


**Fig. 4** (a) Soil N concentration (%), (b) forest floor vegetation PC2, (c) soil water content, (d) forest floor vegetation PC1, (e) slope of the plot, and (f) fire frequency per site, site 1 is in light orange (significant) and site 2 in dark orange (non-significant), as drivers of boreal forest soil C stocks ($\log_e$-scale). Significant model fits from the best model based on the model average analysis are shown for each driver as a solid line with 95% CI. Soil C data are presented as open black dots in all panels except for f, where soil C data are coloured according to site.

## 4. Discussion

We show that soil C stocks are highly variable across fine spatial scales in boreal Scots pine forests, averaging 9.1±0.9 kg $m^{-2}$. This is higher than averages from other comparable study areas in Sweden (2.8±0.1 kg $m^{-2}$, Olsson et al. (2009)) and Denmark (3.9±0.7 kg $m^{-2}$, Vejre et al. (2003)). However, both these studies report shallower organic surface soil layers than what we found across our study area, which is a key-explanation for the discrepancy. Our study provides evidence that the variation in soil C stock sizes is partly attributed to historical forest fires, but even more to contemporary ecosystem productivity, vegetation composition, and fine-scale hydro-topography.

### 4.1 *Role of historical fires*

Typically, increased fire frequency results in larger C losses (Alcaniz et al., 2018; Pellegrini et al., 2018). A significant interaction term revealed that the effect of fire frequency on soil C was not consistent between the two study sites. At the western site 1, soil C expectedly decreased with fire frequency, whereas no such effect was present at the eastern site 2. We propose that the lack of impact of forest fires at site 2 may be explained by: I) low intensity fires; II) organic soil recovery due to long time since last fire events; and III) discrepancies in spatial precision between soil C stock estimates and fire history data.

First, many of the fires in the area may have been low-intensity and anthropogenic prescribed burns, especially after AD 1600 (Storaunet et al., 2013; Rolstad et al., 2017). Historically, summer dairy farmers were known to set fires in spring and early summer to remove old field vegetation while leaving the organic soil layer intact (Larsson, 1995; Niklasson & Drakenberg, 2001). This fire management was to enhance the quality of forest pastures without reducing the long-term productivity of the land. Likewise, a Finnish experimental study, reporting raw humus layers to be remarkably resistant to drought due to strong water-holding capacity (Lindberg et al., 2021). Therefore, many of the fires at site 2 may have had negligible effect on soil C, whereas several large, natural fires may have depleted more of the soil C at site 1.

Second, no fires have been recorded at site 2 over the past 250-300 years, and in addition, after AD 1600 the fire sizes and intensity went significantly down (Storaunet et al., 2013). This suggests that the forest soil C stocks were only lightly depleted and thereafter partly or fully recovered in the time period after last fires. Our finding is consistent with previous studies on soil C recovery time, which have been investigated across chronosequences (Harden et al., 2012; Hume et al., 2016; Palviainen et al., 2020) and differences in fire frequencies in boreal forests (Pellegrini et al., 2018).

On the other hand, studies have also found the recovery of boreal forest soil C stocks to be impacted by historical fire regimes for hundreds to several thousands of years (Wardle et al., 2012; Andrieux et al., 2018). As our record of fires was limited to the last 650 years, soil C stocks may have been more influenced by earlier Holocene fire activity, masking possible effects of more recent fires. Furthermore, besides a direct effect of fire, i.e., that fire consumes organic matter, and removes soil C stocks partly or totally, these studies also found that fire had indirect effects on soil C stocks, through fire driven changes in plant diversity, composition (Wardle et al., 2012), and soil pH (Andrieux et al., 2018).

Third, and possibly most likely, the lack of influence of past fire events at site 2 can be attributed to a mismatch in terms of spatial resolution. Even though Storaunet et al. (2013) have documented the spatiotemporal fire history of the study sites in detail, we have a considerably higher spatial resolution in the present study. Many of the fires may also have burnt the ground vegetation only partially, resulting in a fine-scaled mosaic pattern of burnt and unburnt areas. Such spatial discrepancies could obscure potential relationships between fire occurrences in the past and contemporary soil C stock sizes as the impact of historical fires may be overshadowed by other variables that operate on finer spatial scales. In addition, the dendroecological records of fire events may have missed several low-intensity fires that did not produce fire scars in the trees. Likely, the fire history of our study sites, as well as of most boreal forests, is more spatially complex than can be revealed by standard dendrochronological studies as their spatial precision is directly dependent on the number and distribution of fire scarred trees, see e.g. (Parisien & Moritz, 2009; Rolstad et al., 2017).

### 4.2 *Role of nitrogen and soil texture*

Boreal forests are strongly N limited (Tamm, 1991; DeLuca et al., 2008; Maaroufi et al., 2015), and soil N availability is thus an important indicator of productivity. Our soil total N measures do not necessarily reflect availability. Nonetheless, total N concentration in the soil samples was clearly the most important driver of soil C stock sizes in our study. Results from a long-term N addition experiment give support for a positive relationship between N availability and amount of C in the organic surface soil as N treatments resulted in increasing C pools in the soil O-horizon (Maaroufi et al., 2015). However, the relationship between N availability and C sequestration in boreal forest soils is complex (Hume et al., 2016; Högberg et al., 2017; Mayer et al., 2020), and it is worth noting that the N treatment levels in Maaroufi et al. (2015) was generally high, with yearly doses of 12.5 or 50 kg N $ha^{-1}$, over 16 years.

Productivity and soil C stocks of the boreal forest was also mediated by soil drainage, which have for long been considered a primary control on boreal forest soil C stocks (Harden et al., 1997). In-depth investigation of soil drainage was beyond the scope of this study. Even so, our results suggest that differences in soil texture, especially proportion of silt in the mineral soil, constitutes an important regulator of build-up of organic matter. Moreover, we found differences in slope of each sampling plot to be more important than the slope of the general terrain, highlighting how fine-scale differences need to be accounted for in soil C stock estimations.

### *4.3 Role of contemporary vegetation and hydro-topography*

It is well known that vegetation composition is important in shaping forests and soil C accumulation on wide forest type spatial scales (Jobbágy & Jackson, 2000; Nilsson & Wardle, 2005; Jonsson & Wardle, 2010). Our study adds a further perspective to this context by revealing a strong fine-scale spatial relationship between vegetation composition and soil C stock size within a single and widely distributed boreal forest type, i.e., nutrient poor Scots pine forests with feathermosses and ericaceous dwarf shrubs as dominants in the field- and forest floor vegetation (see Kielland-Lund (1981) for forest type definition).

Whether the forest floor was dominated by feathermosses or *Sphagnum* peatmosses turned out as an important driver of the soil C stocks across fine spatial scales, and peatmoss dominated areas stored the largest amounts of soil C. We attribute this to hydro-topography, and the habitat preferences and ecophysiological characteristics of the different functional groups of mosses. Feathermosses generally prefer drier habitats and have a relatively high decomposability and low productivity compared to peatmosses (Lang et al., 2009), resulting in less C accumulation. In contrast, peatmosses prefer waterlogged habitats, in which they outcompete other vegetation (Van Breemen, 1995; Bisbee et al., 2001). Such wet habitats create an anoxic soil environment with low decomposition rates, resulting in accumulation of organic matter, and thereby C (Ohlson & Halvorsen Økland, 1998). The importance of moss cover and water availability for the C stocks in boreal forests is known from previous studies e.g., (Olsson et al., 2009; Andrieux et al., 2018; Zajícová & Chuman, 2020) and our results underline the general importance of the forest floor vegetation as a driver of the spatial variation in C stocks across fine scales.

Nitrogen availability, which is an important driver soil C stocks (Maaroufi et al., 2015), is also known to be significantly affected by hydro-topographic variability. For example, Woo and Kumar (2017) have shown that both the distributions of concentrations and age of different inorganic nitrogen species including nitrate, ammonia, and ammonium in the soil is linked to micro-topographic variability.

### *4.4 Conclusion*

We conclude that boreal forests soil C stocks, which appear homogenous on large spatial scales, are highly heterogenous across fine spatial scales. Variation in soil C stocks was partly attributed to historical forest fires, but more so to contemporary ecosystem productivity, vegetation composition, and fine-scale hydro-topography. These results highlight the importance of high spatial resolution, as well as controlling for various edaphic and biotic factors when investigating soil C stocks and its drivers.

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## Declaration of interest

The authors report there are no competing interests to declare.

## Data statement

Data associated with this manuscript are deposited in the NMBU Open Research Data database https://doi.org/10.18710/FJWV6X.

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