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Soil charcoal in boreal forests with contrasting management histories in southeast Norway

Daniel Hubner
Master of Science in Ecology

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Abstract

Macroscopic charcoal particles in the soil of boreal forests provide a record of local-scale fire history. They also serve as a long-lived carbon sink and have a positive influence on soil function. However, the distribution of soil charcoal is extremely patchy at small spatial scales, which complicates efforts to quantify the soil charcoal pool precisely. In this project, I investigated the size, variability, parent species composition, and environmental relationships of the soil charcoal pool in boreal forests with contrasting management histories in southeast Norway.

My project is based upon the mass and origin species of charcoal particles found in 113 soil cores collected from 10 pairs of spruce forest plots. The paired plots are as similar as possible except for their past management; one plot in each pair has historically been clear-cut and the other is near-natural. I analyzed 1) the overall size, variability, and species composition of the soil charcoal pool in the project region; 2) differences in the charcoal pools of the paired plots and consequent implications for their site histories; and 3) modeled relationships between the charcoal pool and metrics of climate, terrain, and contemporary forest characteristics. I found an overall mean charcoal content of 168 (± 36) g/m^2, which aligns with past studies in the region; however, within-plot spatial variability was very high, and the plot-level estimates therefore lacked precision. The soil charcoal pool was dominated by spruce charcoal (contrasting with previous results that found pine charcoal to be dominant even at spruce forest sites, as spruce forests became dominant in the region relatively recently in the late Holocene).

There was no overall difference in charcoal content between clear-cut and near-natural plots, but three individual sites exhibited significant differences between their paired plots, and I assessed the potential implications for the site histories of these plots. Finally, I found no relationships between the soil charcoal pool and any climate or terrain metrics, likely due to issues of scale; however, I found a positive relationship between charcoal occurrence and the proportion of (and proximity to) pine forest in the surrounding landscape.

My findings emphasize the importance of fine-scale spatial effects in controlling the soil charcoal pool. Intensive sampling is necessary in order to precisely estimate the average soil charcoal stock even on the scale of a single forest stand; similarly, fine-scale measurement of environmental variables is necessary in order to meaningfully analyze their relationships with the soil charcoal pool. In spite of this, my results identified a significant relationship between charcoal occurrence and forest composition at a broader spatial scale, possibly reflecting an influence of landscape-level species composition on stand-level fire regimes.

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1. Introduction

When fire strikes a forest stand, much of the carbon in the combusted organic material is released directly to the atmosphere as carbon dioxide, but a small proportion is converted to solid particulate residue, i.e., charcoal. This charcoal is then deposited locally on the forest floor and incorporated into the soil. It has been estimated that boreal forest fires typically convert only 2% or less of combusted biomass to charcoal (Clark et al., 1998; Hart & Luckai, 2013), but the soil charcoal pool is ecologically significant despite that low conversion rate. This is because charcoal is substantially more carbon-dense than the original organic material, and is also more resistant to breakdown than other forms of soil organic carbon: in some cases, the mean residence time of charcoal in the soil may even be millennia (de Lafontaine & Asselin, 2011; Makoto & Koike, 2021). This persistent soil carbon pool is of interest for several distinct reasons.

First, because macroscopic charcoal produced by forest fires is overwhelmingly deposited locally rather than dispersed across long distances (Clark et al., 1998; Lynch et al., 2004; Ohlson & Tryterud, 2000), it provides a spatially-precise record of local fire history. The occurrence of macroscopic charcoal particles in the soil of a forest stand strongly indicates that the immediate area has historically burned, and the distribution of charcoal particles in the soil can be expected to reflect site-specific particularities in the position of vegetation and dead wood (i.e., the fuel load) at the time of combustion (Carcaillet & Talon, 2001; Ohlson et al., 2017). Many past studies have therefore examined the macroscopic charcoal content in soil samples in order to reconstruct local-scale fire history reaching back thousands of years (e.g., Bradshaw & Zackrisson, 1990; Horn & Underwood, 2014; Ohlson et al., 2011; Touflan et al., 2010). Carbon dating of charcoal particles and cross-referencing to dendrochronological evidence can enhance the temporal precision in such reconstructions (e.g., Gavin et al., 2003a; Niklasson & Granström, 2000), and identifying the origin species of charcoal particles can provide evidence about historic forest composition and successional changes (e.g., Kasin et al., 2017; Touflan et al., 2010). The soil charcoal pool thus offers an invaluable record of site-specific ecological history.

Second, beyond providing a record of local history, the boreal soil charcoal pool is also important for global carbon accounting. Boreal forests are a major carbon sink, storing substantially more carbon (both in total and per area) than either temperate or tropical forests (Malhi et al., 1999); precise estimates differ but it is clear that a significant proportion of the world's total terrestrial carbon stock is found in boreal forests. Moreover, the great majority of this boreal forest carbon stock--up to 85%--is located in the soil rather than in aboveground vegetation (Lal, 2005). Carbon-dense charcoal, in turn, may itself constitute around 8-10% of total soil carbon in boreal forests (Hart & Luckai, 2013). Although this is a minority fraction of total soil carbon, it is still highly significant in aggregate: Ohlson et al. (2009) estimated that a total of approximately 1 Pg of carbon is contained in the soil charcoal of the world's boreal forests, an amount equivalent to about 15% of annual anthropogenic emissions from fossil fuel burning. Along similar lines, Jones et al. (2019) suggested that cumulative global pyrogenic charcoal production since 1750 could be equivalent to as much as 40% of the anthropogenic carbon emissions due to land use change over the same period (although this figure is not specific to boreal forests). Clearly, the soil charcoal pool should not be neglected in global carbon accounting efforts.

Third, the presence of charcoal is known to have positive ecological effects for soil function. This is due particularly to the porous physical structure of charcoal particles: their high surface area and high adsorptive capacity can enhance water and nutrient retention and ion exchange capacity, reduce the impacts of inhibitory compounds, promote soil microbial activity, and potentially enhance tree regeneration and growth (Makoto & Koike, 2021; Wardle et al., 1998; Zackrisson et al., 1996). These effects are not universal, but rather may depend on the specific parent material of the charcoal and the particular combustion conditions that produced it (Michelotti & Miesel, 2015; Pluchon et al., 2015). They may also depend on the age of the charcoal, with functional capacities declining over time but potentially being reactivated by heating in subsequent fires (Hyväluoma et al., 2022; Zackrisson et al., 1996). Thus soil charcoal is significant not only for its roles as a historic record and a carbon stock, but also because it plays an important and highly context-specific role in ecological functioning.

However, while the importance of the boreal soil charcoal pool is clear, efforts to understand its magnitude and distribution (and in turn, the extent of its functional and carbon storage roles) are complicated by the fact that it exhibits a very high degree of spatial variability. Because charcoal particles are deposited locally and reflect details of site-specific vegetation conditions (as discussed above), the soil charcoal pool is extremely patchy at very fine (as well as regional) scales (Ohlson et al., 2009; Touflan & Talon, 2009). In fact, soil charcoal content has been found to vary as much as 50-fold over distances as low as 10 cm, with extremely charcoal-rich "hot spots" occurring in very close proximity to soil containing little or no charcoal (Ohlson et al., 2013). It is therefore difficult to precisely estimate--much less predict--the typical magnitude of the soil charcoal pool (and its associated carbon stock) in a given area. This patchiness also bears upon the functional effects of soil charcoal, because it has been shown that plant responses to charcoal are dose-dependent in a manner that is sensitive to small-scale heterogeneity in charcoal amounts (Gale & Thomas, 2021).

In light of this high variability and associated uncertainties, past studies have explored the major factors controlling spatial differences in soil charcoal occurrence. Considerations of climate, terrain/topography, and vegetation conditions are all relevant, and bear upon both production and deposition/accumulation of pyrogenic charcoal. Climate factors (e.g., temperature and moisture) determine fire occurrence (and thus charcoal production) on the scales of short-term weather events, seasonal weather patterns, and long-term climate norms (McLauchlan et al., 2020). Topography influences both charcoal production and deposition: regarding production, fire tends to occur more frequently on south-facing slopes (in the northern hemisphere) and on convex terrain (Bountzouklis et al., 2022; Gavin et al., 2003b; Zackrisson, 1977). Topography can also determine flaming versus smoldering fire behavior (Kane et al., 2010), which in turn are associated with drastically different levels of charcoal production (MacDonald et al., 1991). On the other hand, regarding deposition, charcoal particles can be expected to experience greater erosive transport on steep slopes, and to accumulate at low slope positions and in micro-topographical depressions (Kasin et al., 2017; Rumpel et al., 2006). Finally, vegetation conditions not only determine the density and positioning of the fuel load (as discussed above), but can also shape the local fire regime directly: for example, Ohlson et al. (2011) demonstrated that forest species composition (specifically, the historical invasion of spruce replacing formerly pine-dominated boreal forests) exerts control over fire regimes even independently of climate. The complexity of these interacting factors emphasizes that detailed investigation is required in order to meaningfully understand the variability of the soil charcoal pool.

In this context, the present study examines the characteristics of the soil charcoal pool in the boreal forests of southeast Norway as part of the broader research project "EcoForest." EcoForest is a research collaboration between the University of Oslo (UiO), the Norwegian University of Life Sciences (NMBU), the Norwegian Institute of Bioeconomy Research (NIBIO), and the Norwegian Institute for Nature Research (NINA) which aims to investigate the long-term ecological effects of clear-cut forestry by comparing paired forest plots, where one plot in each pair has previously been clear-cut and one has not. This management difference does not directly bear upon the soil charcoal pool (because charcoal-producing historic fires occurred long before recent clear-cut management), but investigating soil charcoal at the EcoForest plots enables this study to take advantage of additional site-specific data that has been gathered as part of the broader project, and in turn, the site history inferred from the charcoal record can provide further background data on the project's study plots. Specifically, I seek to investigate three primary questions with this study:

1. What is the average magnitude of the soil charcoal pool in the project region, and what is its variability? I expect the mean to be around 100 to 200 g/m^2, which has been suggested as a typical range for boreal forest soils (Ohlson & Tryterud, 2000; Preston & Schmidt, 2006). I also expect to find substantial variability in charcoal content both within and between study plots.

2. What can be inferred about the site histories of the paired EcoForest plots based upon their soil charcoal records? I expect that the paired plots will exhibit no significant differences in their soil charcoal stocks (either overall or for individual pairs), and that the individual pairs will have similar charcoal origin species compositions, reflecting similar site histories in terms of forest composition and fire regime.

3. What relationships can be identified between the soil charcoal pool and other environmental variables measured for the project plots? I expect that metrics of climate, terrain, and/or contemporary forest characteristics may be predictive of the occurrence and amount of macroscopic soil charcoal.

2. Materials and Methods

2.1 Study sites

This project's study sites are located in Innlandet and Viken Counties in southeast Norway (Figure 1). The sites consist of 10 paired plots (for a total of 20 plots). For each site pair, one plot is near-natural (henceforth "NN") and has never been subjected to clear-cut management. The other plot in each pair was clear-cut in the mid 20th century (henceforth "CC"). Each pair was chosen to be as similar as possible in every respect apart from this difference in historic management (e.g., similar vegetation composition, topography, soil characteristics, etc.).

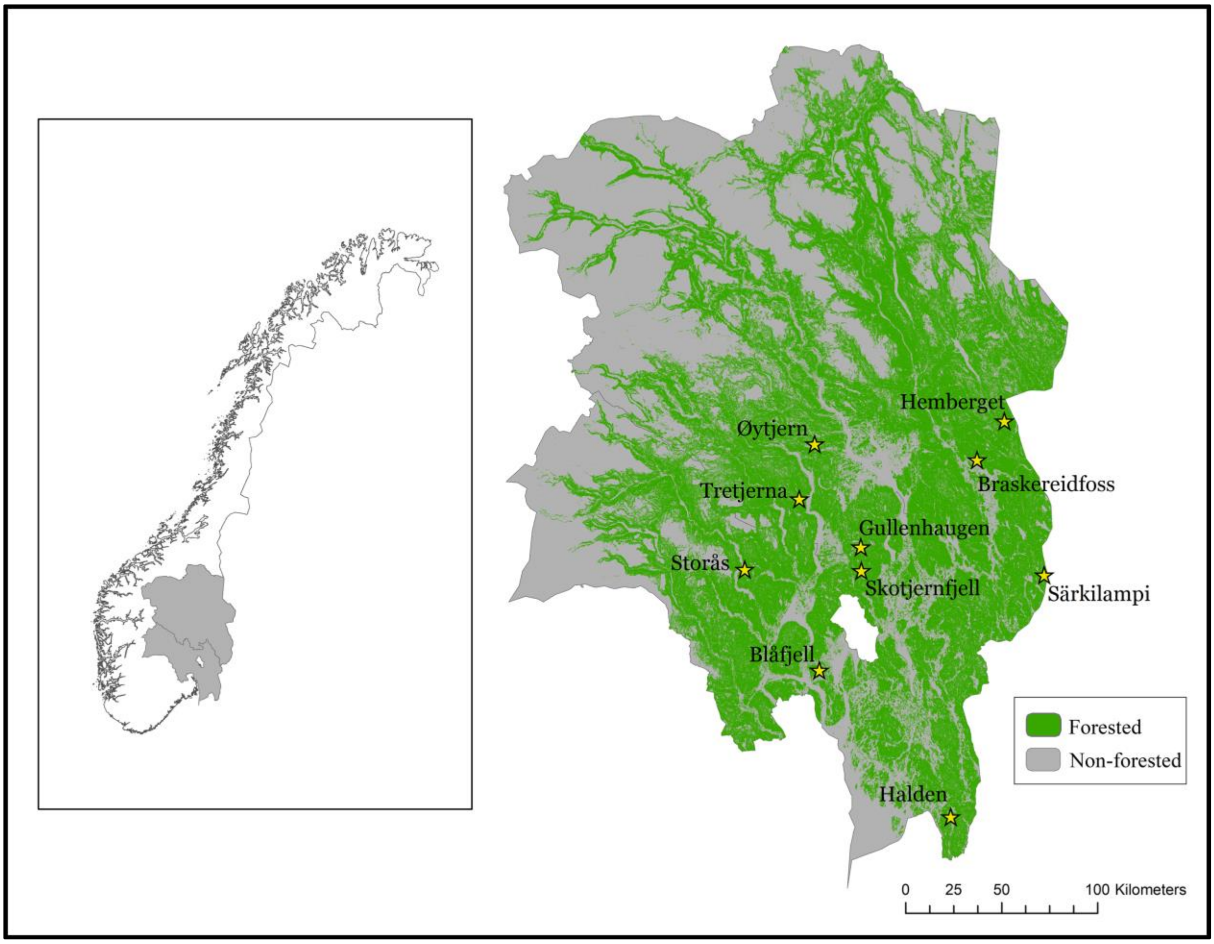

Figure 1. Locations of the study sites within the forests of Innlandet and Viken Counties, southeast Norway. Each site consists of two plots, which are not depicted separately at this scale. Inset national map shows the location of Innlandet and Viken counties in Norway. County boundaries from Kartverket. Forested area from SR16 raster, NIBIO.

The sites are distributed throughout an area of approximately 200 km north-south and 150 km east-west. Plot elevations range from approximately 200 m to 670 m above sea level. Mean annual temperature ranges from approximately 0.5° C to 5.4° C (at the northernmost and southernmost sites respectively). The forest composition at all plots is strongly dominated by Norway spruce (*Picea abies*). Birch (*Betula* sp.) also occurs frequently in smaller numbers; Scots pine (*Pinus sylvestris*) and rowan (*Sorbus aucuparia*) occur only rarely (at two plots and one plot, respectively).

As part of the EcoForest project, the sites were already established and the plot design was already implemented prior to commencement of this study. Each of the 20 study plots is established in a gridded area 15 m × 15 m in size. Within each plot, six subplots have been sited by randomization along the grid (Figure 2). At each subplot, equipment has been placed to measure variables such as temperature, soil respiration, litter decomposition, and others. This study's sampling positions were determined by reference to the marked boundaries of existing biomass and vegetation measurement zones at each subplot.

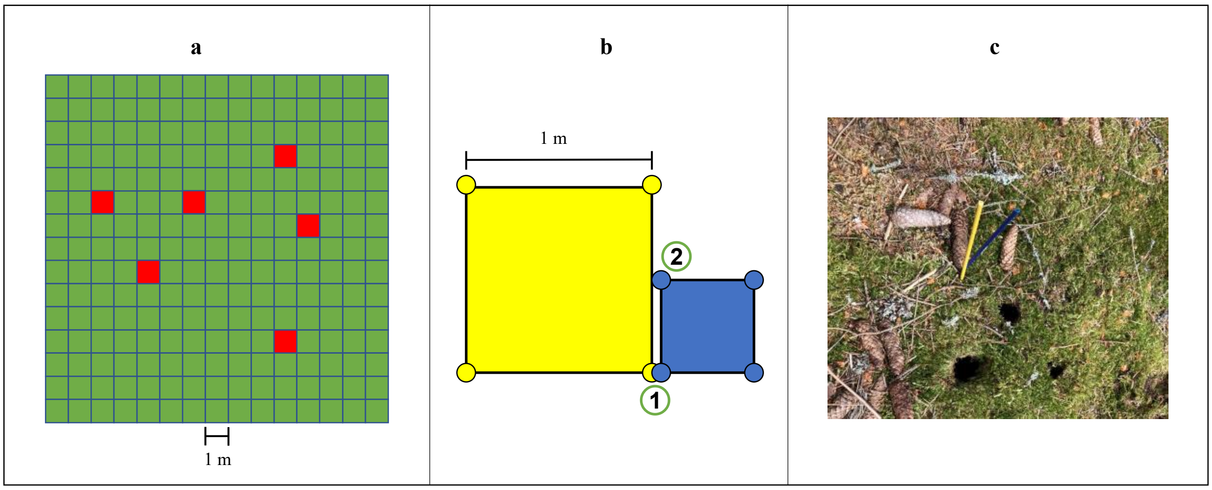

Figure 2. Illustrations of plot layout and soil sampling location. **a.)** Standard layout of an EcoForest plot. Within the 15 m × 15 m grid (green squares), six subplots are positioned according to random coordinates (red squares). **b.)** This project's soil sampling location within a subplot, determined by reference to existing marked measurement areas for vegetation (yellow) and biomass (blue). Standard sample position is labeled "1," alternate sample position is labeled "2." **c.)** Field example of the standard sample position in relation to vegetation and biomass marker sticks (the sample hole at bottom left is for this project; the two nearby smaller holes are from a different project).

2.2 Sample collection

I visited the 20 study plots during May and June of 2022 to collect soil samples. I used a soil corer with an inner diameter of 6 cm to take one soil sample from each subplot (resulting in a total of 120 soil cores for my project). My standard sample position was at the location marked "1" on Figure 2 above, just below the intersection of the previously-established biomass and vegetation measurement plots (which are marked in the field with colored sticks). If my initial soil sample failed (e.g., due to buried roots or rocks), I repositioned approximately 15 cm backward (moving away from the biomass and vegetation plots) as a general rule, although ground conditions and equipment placement sometimes required shifting in other directions. If broader ground conditions (such as large exposed roots, shallow bedrock, etc.) clearly did not allow soil sampling at all near the primary position, I instead took my sample at the secondary location marked "2" on Figure 2.

For each soil sample, I aimed to collect the entire organic soil layer as well as the first few centimeters of the mineral layer, because macroscopic charcoal is known to accumulate mainly at the organic-mineral interface (Ohlson et al., 2009; Preston et al., 2017). I determined the appropriate depth by sound and texture (i.e., the soil corer sounds and feels "crunchy" upon reaching the mineral soil), and checked each soil core visually to confirm that the mineral layer had been reached. After extracting the soil core, I recorded the depth (in centimeters) of the entire sample as well as the depth of the organic layer; these measurements were made in the hole the sample was taken from rather than along the length of the soil core itself, because the cores may have experienced compression during sampling.

I stored each soil core in a small paper bag with its cylindrical shape intact. After each field sampling session, I brought the sample bags to NMBU and placed them in a drying oven at 30° C. The samples dried in the oven for a minimum of one week, after which they were stored at room temperature until my laboratory work began.

2.3 Laboratory analysis

2.3.1 Charcoal separation and weighing

I conducted my laboratory work at NMBU from September through November 2022. I separated all macroscopic charcoal particles from the 120 soil cores using a manual hand-picking method; this simple technique is known to successfully identify most of the soil charcoal content by mass (Ohlson et al., 2009, supplementary information). For each soil core, I transferred a few centimeters of material at a time into a glass petri dish and sorted through it with tweezers under a magnifying lamp with 3× magnification, visually identifying all charcoal particles and transferring them into a glass vial (Figure 3). I inspected the entirety of each soil core, moving from the mineral portion up to the litter layer. If it was unclear whether a particle was charcoal or not, I lightly rubbed it on white paper (because charcoal leaves a black charred streak), examined it at higher magnification under a microscope, and/or consulted with my supervisors. I also recorded qualitative notes about the samples when relevant (e.g., noting the presence of especially large pieces of charred material, noting the occurrence of significant amounts of charcoal outside the expected organic-mineral interface area, etc.). Once I had finished separating the macroscopic charcoal from all 120 soil samples, I measured the mass (to a precision of 0.0001 grams) of the charcoal from each sample with a high-precision analytical balance (Sartorius model ED224S).

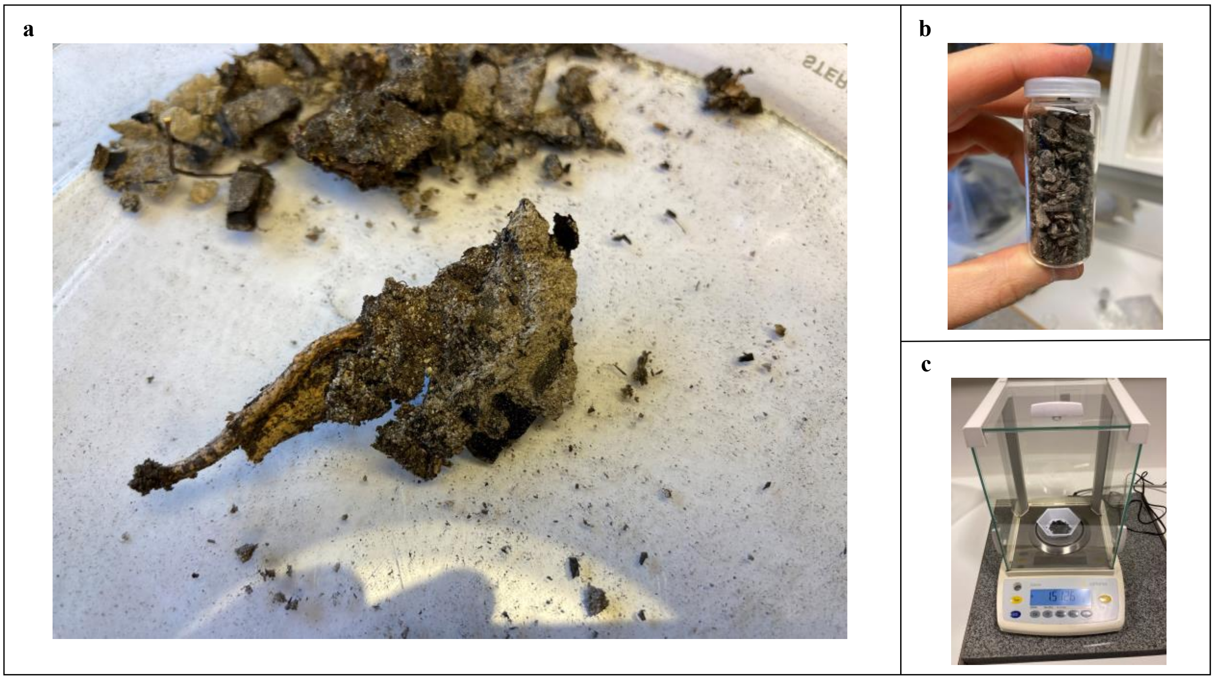

Figure 3. **a.)** A small portion of mineral soil with obvious charcoal particles (black) viewed through the magnifying lamp during hand sorting. **b.)** Vial containing all charcoal particles separated from a soil sample. **c.)** A charcoal sample being weighed.

Based on visual inspection of the dried soil samples during the hand sorting process, I determined that seven of the soil cores had not actually reached the organic-mineral soil interface. Therefore, I excluded these failed samples from my analysis, resulting in a final sample count of N = 113 for this project. The seven failed samples were distributed between five plots (Skotjernfjell CC, both Øytjern plots, and both Halden plots), with a maximum of two failed samples from any single plot.

2.3.2 Charcoal species identification

After I finished separating and weighing my charcoal samples, I packaged the charcoal vials for transport and shipped them to an external laboratory (Vedlab, located in Falun, Sweden) for charcoal species identification. There were 65 samples containing macroscopic charcoal; two sample vials broke in transit, leaving 63 charcoal samples to be analyzed. Vedlab's species analysis was conducted by Erik Danielsson, and consisted of visual analysis under a microscope at up to 625× magnification. He generally analyzed approximately 30 charcoal pieces from each plot, evenly distributed among the subplot samples. For plots where more than one tree species occurred among those pieces, he analyzed an additional 10 pieces per species. For some plots the total amount of charcoal in the samples was not enough to reach these numbers, therefore a smaller number of pieces were analyzed in some cases. In total, 512 charcoal pieces were analyzed.

The results provided by Vedlab listed the number of analyzed charcoal pieces by tree species for each subplot sample (as well as the total mass of the analyzed pieces for that subplot). I transcribed the counts of analyzed charcoal pieces from Vedlab's report into a Microsoft Excel file and summed them by species at the site and plot levels.

2.4 Data analysis

I conducted my data analysis with R version 4.1.2 (R Core Team, 2021) in RStudio 2022.12.0 (Posit Team, 2022). For geospatial data processing I used ArcGIS Desktop 10.8.1 (Esri, 2020) with the Spatial Analyst extension. For model building and assessment I used the "lme4" (Bates et al., 2015), "lmerTest" (Kuznetsova et al., 2017), and "performance" (Lüdecke et al., 2021) packages in R.

2.4.1 Characterizing and comparing soil charcoal stocks

My analysis began with the raw data of charcoal mass recorded for each sample during my laboratory work. I also added a binary indicator of charcoal presence for each sample (1 = charcoal present; 0 = no charcoal present). Then I converted the raw charcoal mass to a charcoal amount in grams per square meter, based upon the area of the 6 cm diameter (3 cm radius) soil corer:

$$\text{Charcoal amount (g/m}^2\text{)} = \text{Charcoal mass (g)} / ((\pi \times 3^2) / 10000)$$

I then calculated the mean, standard error, standard deviation, minimum, and maximum of the charcoal amount at the levels of 1) the whole project (i.e., all samples); 2) CC and NN samples respectively; and 3) individual plots. I also calculated the proportion of samples with charcoal present (based on the binary variable mentioned above) and charcoal species proportions (based upon the species counts received from Vedlab).

I statistically tested for differences in charcoal amount between CC and NN plots, project-wide and also individually for each of the 10 site pairs. My data were not normally distributed, therefore I used the non-parametric Kruskal-Wallis test for this purpose.

2.4.2 Modeling relationships between soil charcoal and environmental variables

I fitted models of both 1) charcoal amount (in grams per square meter) and 2) likelihood of charcoal presence (i.e., the binary indicator mentioned above) using a large set of potential explanatory variables which are discussed further below. I also inspected scatter plots to visually/qualitatively assess the relationship between sample charcoal amount and the predictor variables. For the models of charcoal amount I used mixed effects linear regression, with a logarithmic transformation applied to the charcoal amount because my data violated the linear regression assumptions of linearity and normality of residuals. The logarithmic transformation was:

$$\log(\text{Charcoal amount } (g/m^2) + 1)$$

The addition of a small constant of 1 accounted for the many zeroes in the data (i.e., zero values then log transformed to zero) without majorly impacting the log transformation of the non-zero values (because no non-zero sample had an untransformed charcoal amount lower than 1 g/m^2). For the models of likelihood of charcoal presence I used mixed effects logistic regression with the binary charcoal presence indicator as the dependent variable. In both the linear and logistic models, plot and site were included as random effects (with plot nested within site).

The potential predictor variables I examined included measures of climate, terrain, and contemporary forest characteristics in the area surrounding each study plot. These variables came from three general sources. The first source was field measurements taken at the project plots as part of the broader EcoForest project. The variables I used from this source were at-plot forest density (measured by relascope) and species proportions of inventoried trees. The relascope measurements were recorded by various members of the EcoForest project during establishment of the plots, and the tree inventory information was gathered for the project by the forestry consulting firm NORSKOG. Because all the project plots are strongly dominated by spruce, I calculated these at-plot tree species proportions only to the level of spruce versus non-spruce, and used the non-spruce proportion as a potential predictor variable.

The second source of potential predictor variables was climate and terrain data that was modeled for each of the plots. The majority of this modeled data was at 100 m resolution and was produced by Peter Horvath for the EcoForest project (see Table 1 for a list of the climate and terrain metrics from this source). In addition to this pre-existing modeled data, I calculated the average heat load index for each plot at 15 m scale using a digital terrain model (1 m resolution, available from Kartverket) and the "ArcGIS Geomorphometry & Gradient Metrics" toolbox (Evans et al., 2014). (I used a 15 m scale after initially calculating heat load index at 100 m scale to match the other modeled data, but finding that its average converged to 0.5 and exhibited virtually no variation when calculated at that larger scale.)

The third source of potential predictor variables was remotely-sensed data on contemporary forest characteristics in the area surrounding each plot. This data came from the "SR16" forest resource spatial dataset (16 m resolution, available from NIBIO). I utilized the SR16 rasters for dominant tree species, site index, and forest density for Innlandet and Viken Counties. I also utilized dominant species information from the separate SR16 vector dataset, which aggregates the raster species data to delineate larger-scale area polygons typified by a particular dominant species.

In order to investigate potential relationships with the SR16 variables on varying scales, I summarized them separately within circular buffers with radii of 100 m, 250 m, 500 m, and 1000 m respectively around each plot. To summarize site index and forest density, I calculated their average raster values within each buffer. For dominant tree species, I summed the number of raster cells of each type (spruce, pine, or deciduous) within each buffer, then calculated the proportions between them and utilized the pine proportion as a potential explanatory variable. Lastly, I used the vector version of the SR16 dataset to calculate the distance from each plot to the nearest pine-dominant forest polygon. Complete details on the ArcGIS geoprocessing steps used for these calculations are included in the Appendix.

A full list of the potential explanatory variables I considered in this modeling exercise is provided in Table 1, with notes indicating which of the above-mentioned sources each variable was derived from.

Table 1. List of all potential explanatory variables tested as fixed effects in regression models. The variables are measures of climate, terrain, or contemporary forest characteristics in the area around each study plot.

Variable	Units	Source
Mean annual temperature	° C	Horvath environmental modeling
Annual precipitation	mm	Horvath environmental modeling
Proximity to coast	km	Horvath environmental modeling
Terrain curvature index (classed categorically as positive, negative, or flat)	n/a	Horvath environmental modeling
Slope	n/a	Horvath environmental modeling
Vertical distance to channel network	m	Horvath environmental modeling
Topographic wetness index	n/a	Horvath environmental modeling
Terrain ruggedness index	n/a	Horvath environmental modeling
Heat load index	n/a	Calculated from digital terrain model
Proportion non-spruce at plot	%	NORSKOG plot surveys
Forest density at plot	m^2/ha	Existing relascope measurements
Proportion pine in surrounding buffer, 100 m radius	%	Calculated from SR16 treslag raster
Proportion pine in surrounding buffer, 250 m radius	%	Calculated from SR16 treslag raster
Proportion pine in surrounding buffer, 500 m radius	%	Calculated from SR16 treslag raster
Proportion pine in surrounding buffer, 1000 m radius	%	Calculated from SR16 treslag raster
Average site index in surrounding buffer, 100 m radius	n/a	Calculated from SR16 bonitet raster
Average site index in surrounding buffer, 250 m radius	n/a	Calculated from SR16 bonitet raster
Average site index in surrounding buffer, 500 m radius	n/a	Calculated from SR16 bonitet raster
Average site index in surrounding buffer, 1000 m radius	n/a	Calculated from SR16 bonitet raster
Average density in surrounding buffer, 100 m radius	m^2/ha	Calculated from SR16 grunnflate raster
Average density in surrounding buffer, 250 m radius	m^2/ha	Calculated from SR16 grunnflate raster
Average density in surrounding buffer, 500 m radius	m^2/ha	Calculated from SR16 grunnflate raster
Average density in surrounding buffer, 1000 m radius	m^2/ha	Calculated from SR16 grunnflate raster
Distance to nearest pine-dominated forest polygon	m	Calculated from SR16 vector

I first tested each potential explanatory variable individually (i.e., as the only fixed effect in a model) to assess its relationships with charcoal amount and charcoal presence. I intended that when a variable was significant as a fixed effect (at a significance level of 0.05), I would subsequently include that variable in a more complex model with multiple predictors, and ultimately assess multiple candidate models in order to determine the overall best-fit multivariate models for charcoal amount and likelihood of charcoal presence respectively. However, it was not ultimately possible to proceed to testing models with multiple fixed effects, due to a general absence of significant relationships with the potential predictors as well as collinearity between the few predictors that were identified as significant (see the Results section below).

3. Results

3.1 Amount, variability, and species composition of macroscopic soil charcoal

The overall project mean (± 1 SE) charcoal amount was 168 (± 36) g/m^2. For CC plots alone the mean was 155 (± 51) g/m^2, and for NN plots alone the mean was 181 (± 52) g/m^2. The individual plot means ranged from zero (at both Gullenhaugen plots) to 625 (± 268) g/m^2 at Tretjerna CC. Individual samples contained charcoal amounts ranging from zero (which occurred at many plots) to 1843 g/m^2 at Braskereidfoss CC. Figure 4 shows the sample amounts and plot means for all samples and plots.

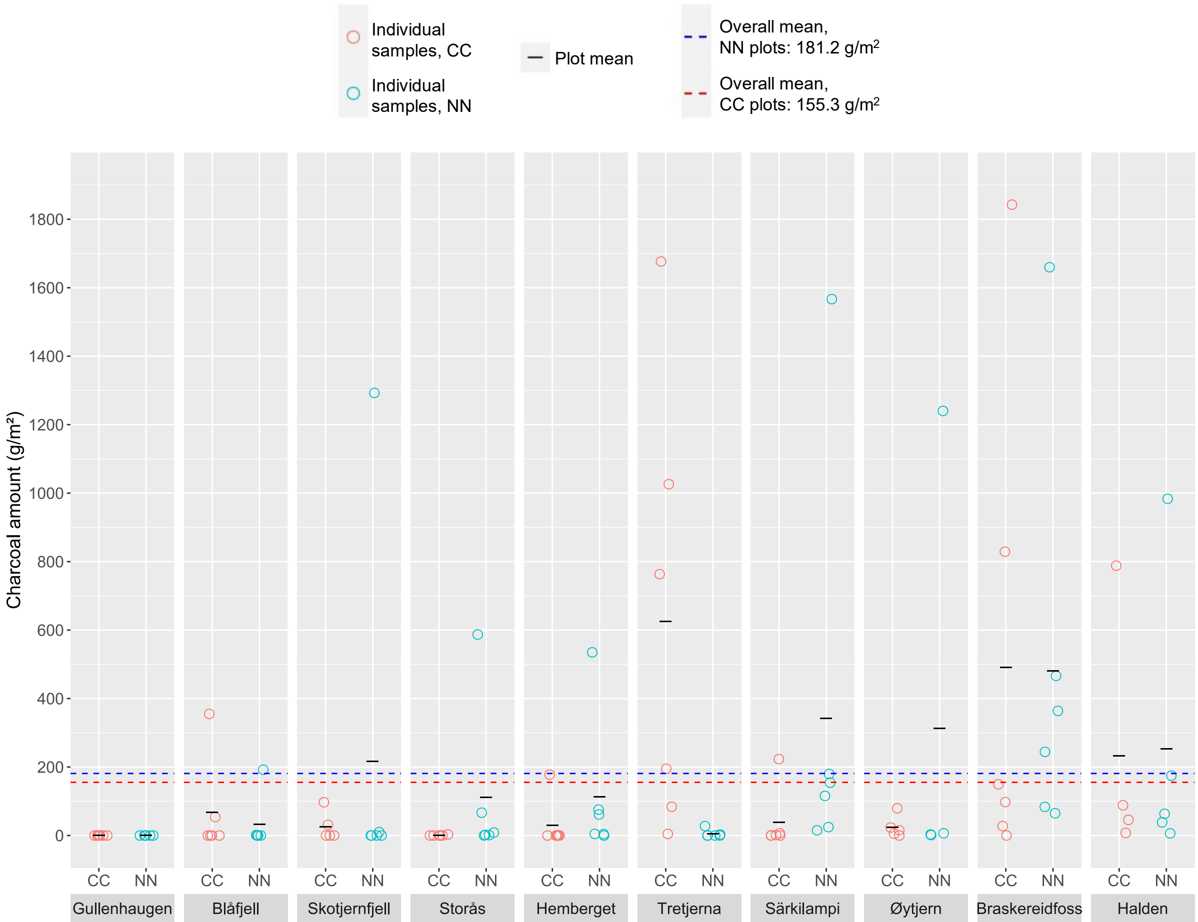

Figure 4. Summary of charcoal amount findings by site and plot. Sites are ordered left to right according to their proportion of samples with charcoal present (i.e., 0% of samples at Gullenhaugen contained charcoal; 100% of samples at Halden contained charcoal). Horizontal dashed lines indicate the project-wide means for CC and NN plots, black lines indicate plot means, circles indicate individual sample amounts.

Soil charcoal amount displayed a very high degree of variability at fine (subplot) as well as regional (project-wide) scales. Sample charcoal amounts were dispersed widely around their respective plot means, and plot means were dispersed widely around the project-wide mean, as shown in Figure 4. For all plots at which charcoal was present, the standard deviation of the charcoal amount was larger than the plot mean; similarly the standard error of the mean estimate was generally on the same order of magnitude as the mean estimate itself. Table 2 summarizes quantitative information on charcoal amount and variability for each plot.

Table 2. Summary of charcoal amounts and variability (mean, median, standard deviation, minimum, and maximum), proportion of samples containing charcoal, and dominant charcoal species for all individual study plots. Project-wide summaries for CC plots, NN plots, and all plots follow at bottom.

	Macroscopic charcoal amount (g/m^2)						
Site	**Mean (SE)**	**Median**	**Std. dev.**	**Min.**	**Max.**	**Charcoal presence (% of samples)**	**Dominant charcoal species**
Gullenhaugen CC	0 (0)	0	0	0	0	0%	n/a
Gullenhaugen NN	0 (0)	0	0	0	0	0%	n/a
Blåfjell CC	68 (58)	0	142	0	355	33%	Spruce
Blåfjell NN	32 (32)	0	78	0	192	33%	Spruce
Skotjernfjell CC	26 (19)	0	42	0	97	40%	Spruce
Skotjernfjell NN	217 (215)	0	527	0	1293	33%	Spruce
Storås CC	0.5 (0.5)	0	1	0	3	17%	Pine*
Storås NN	111 (96)	5	235	0	587	83%	Spruce
Hemberget CC	30 (30)	0	73	0	178	17%	Spruce
Hemberget NN	113 (85)	33	209	0	535	83%	Spruce
Tretjerna CC	625 (268)	479	655	5	1677	100%	Spruce
Tretjerna NN	5 (5)	0	11	0	28	33%	Spruce
Särkilampi CC	38 (37)	0.6	91	0	223	50%	Pine
Särkilampi NN	343 (246)	135	603	15	1567	100%	Pine
Øytjern CC	25 (14)	15	32	0	79	80%	Spruce
Øytjern NN	313 (309)	5	618	1	1240	100%	Spruce
Braskereidfoss CC	491 (298)	124	731	0	1843	83%	Spruce
Braskereidfoss NN	480 (244)	304	598	65	1660	100%	Spruce
Halden CC	232 (186)	67	372	7	788	100%	Pine
Halden NN	253 (185)	63	413	6	984	100%	Pine
All CC plots	*155 (51)*	*0.6*	*384*	*0*	*1843*	*50%*	*Spruce*
All NN plots	*181 (52)*	*6*	*395*	*0*	*1660*	*65%*	*Spruce*
All plots	**168 (36)**	**4**	**388**	**0**	**1843**	**58%**	**Spruce**

* Note that at Storås CC there was only one piece of charcoal analyzable for its species, therefore "dominant charcoal species" has little meaning at this plot.

Charcoal presence (as a binary indicator) also displayed a high degree of variability at the plot level. Out of the 113 total samples, 48 (42%) contained no macroscopic charcoal at all. Samples with charcoal present and absent were generally intermixed within single plots. Only two plots (both at Gullenhaugen) had no charcoal in any of their samples. Six plots had charcoal present in all of their samples (Tretjerna CC, Särkilampi NN, Øytjern NN, Braskereidfoss NN, and both Halden plots). The majority, 12 plots, had a mix of samples with charcoal present and absent. The proportion of samples with charcoal present is indicated for each plot in Table 2 above.

The charcoal species analysis showed that Norway spruce (*Picea abies*) charcoal was generally dominant throughout the project. Of the 18 plots for which charcoal was present (i.e., all plots except the pair at Gullenhaugen), spruce charcoal was identified in some amount at 16 of them, and was the most dominant species at 13 of those. At the five plots which were not dominated by spruce charcoal, Scots pine (*Pinus sylvestris*) was instead the dominant charcoal species (Storås CC, both Särkilampi plots, and both Halden plots). Charcoal from five deciduous taxa was also identified in generally small quantities at a small number of plots, but was not dominant at any plot. The five deciduous taxa were birch (*Betula* sp.) at four plots, willow (*Salix* sp.) at three plots (and in notably large quantity at Tretjerna CC), and alder (*Alnus* sp.), hazel (*Corylus avellana*), and rowan (*Sorbus* sp.) at one plot each. Table 2 lists the dominant charcoal species at each plot; Figure 5 shows species proportions at the site level.

Figure 5 summarizes these results at the site (rather than plot) level in geographic context. There are no evident regional-scale geographic patterns in the frequency of charcoal presence or the proportions of charcoal origin species.

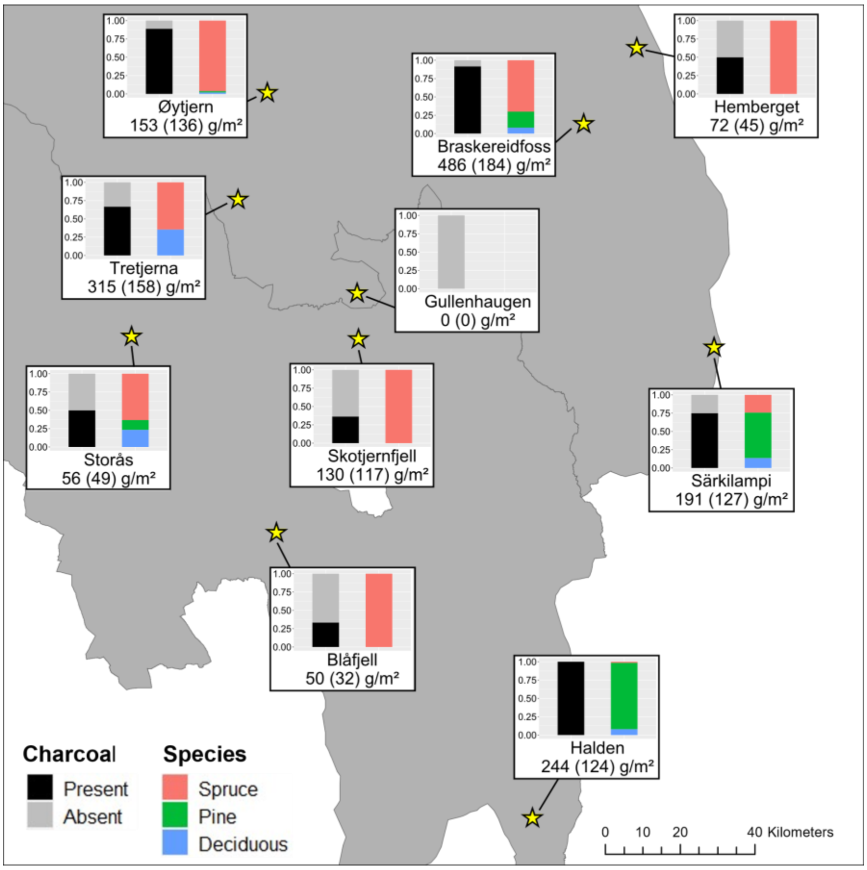

Figure 5. Site-level (i.e., paired plots combined) results in geographic context. Inset panels depict the proportion of samples with charcoal present vs. absent (black and gray bars) and the proportions of identified charcoal species (colored bars). Site mean charcoal amount (with standard error in parentheses) appears below the site name. Gray background indicates Innlandet and Viken County boundaries.

3.2 Comparison of clear-cut and near-natural plots

Overall, the difference in mean charcoal amount between CC and NN plots was not significant, and the same was true for seven of the 10 site pairs individually (Table 3). However, for three of the sites there was a significant difference in charcoal amount between the paired plots: Storås ($p = 0.033$), Tretjerna ($p = 0.006$), and Särkilampi ($p = 0.036$). The NN plots had higher charcoal content at Storås and Särkilampi; the CC plot had higher charcoal content at Tretjerna (and in fact Tretjerna CC had by far the highest mean charcoal amount out of all plots project-wide).

Table 3. Results of Kruskal-Wallis tests for differences in charcoal amount between CC and NN plots at each study site and project-wide (bottom).

Site	H-value	p
Gullenhaugen	n/a	n/a
Blåfjell	0.036	0.849
Skotjernfjell	0.045	0.833
Storås	4.565	0.033
Hemberget	3.221	0.073
Tretjerna	7.679	0.006
Särkilampi	4.395	0.036
Øytjern	0.060	0.807
Braskereidfoss	0.231	0.631
Halden	0.000	1.000
All sites	**1.209**	**0.272**

Figure 6 compares the charcoal species proportions (based on the analysis from Vedlab) at the paired plots. In general the charcoal species composition is quite similar between the CC and NN plots for each site. A notable exception is Tretjerna, where a significant amount of willow (*Salix* sp.) charcoal was identified at the CC plot, whereas only spruce was found at the NN plot. Nonetheless, all site pairs had the same dominant charcoal species at both plots (except Storås, which should be interpreted with caution because there was only one piece of charcoal analyzable by Vedlab for the whole CC plot).

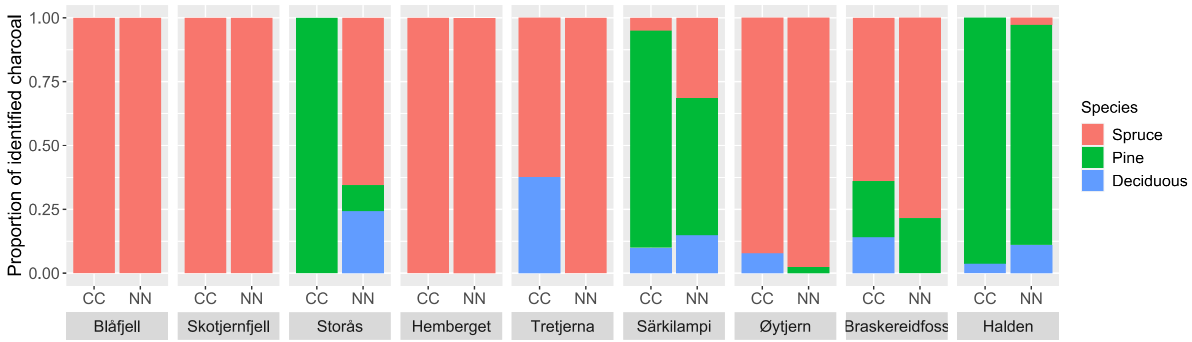

Figure 6. Comparison of proportions of identified charcoal species for each site pair (Gullenhaugen is not shown because no charcoal was found). The combined deciduous category includes birch, willow, alder, hazel, and rowan. Note that there was only one piece of analyzable charcoal at Storås CC.

3.3 Modeled relationships between soil charcoal and environmental variables

The majority of the potential explanatory variables tested in the regression models had no significant relationships with either charcoal amount (logarithmically transformed) or charcoal presence (as a binary indicator). Complete results from the tested models for all potential predictor variables are included in the Appendix. None of the tested climate or terrain metrics were significantly predictive of charcoal amount or presence. Of the variables describing contemporary forest characteristics, measures of pine prevalence in the surrounding area were significant and are discussed below; no other variables (i.e., site index or forest density at any scale) were significant.

Charcoal amount (logarithmically transformed) had a significant relationship with three measures of contemporary pine prevalence. It had a positive relationship with proportion pine within the surrounding 100 m buffer and proportion pine within the surrounding 250 m buffer, and a negative relationship with the distance to the nearest pine-dominated stand (Table 4). However, although these pine variables were significant as fixed effects, they explained only a small proportion of the variation in charcoal amount (see the low marginal R^2 values for all three effects in Table 4). The full models (inclusive of the random effects of plot and site) also left the majority of the variation in charcoal amount unexplained (i.e., conditional R^2 values below 0.5).

Table 4. Significant predictors from mixed effects linear regression models of logarithmically transformed charcoal amount. Plot and site (nested) are random effects in all models. Marginal R^2 indicates the explanatory power of the fixed effect; conditional R^2 indicates the explanatory power of the full model.

Predictor	**Estimate**	**SE**	**t-value**	**p**	**Marg. R^2**	**Cond. R^2**
Proportion pine within 100 m buffer	11.133	5.189	2.146	0.045	0.091	0.405
Proportion pine within 250 m buffer	6.808	2.689	2.532	0.024	0.126	0.408
Distance to nearest pine-dominated area	-0.005	0.002	-2.517	0.030	0.130	0.413

The same three measures of pine prevalence were significantly more explanatory in their relationships with charcoal presence as a binary variable. There was again a positive relationship with proportion pine within the surrounding 100 m buffer, and the explanatory power of both the fixed effect and the full model were more substantial (Table 5). There was also a positive relationship with proportion pine within the surrounding 250 m buffer, but the explanatory power of the model was lower than at 100 m. Lastly, there was again a negative relationship with distance to the nearest pine-dominated stand, but with further reduced explanatory power compared to the pine proportion models. However, all three models of charcoal presence were more powerful than any of the models of charcoal amount discussed above. Figure 7 depicts the predictions of these charcoal presence models, reflecting an increasing likelihood of charcoal occurrence when pine is increasingly present in the surroundings.

Table 5. Significant predictors from mixed effects logistic regression models of likelihood of charcoal presence. Plot and site (nested) are random effects in all models. Marginal R^2 indicates the explanatory power of the fixed effect; conditional R^2 indicates the explanatory power of the full model.

Predictor	**Estimate**	**SE**	**z-value**	**p**	**Marg. R^2**	**Cond. R^2**
Proportion pine within 100 m buffer	31.452	14.273	2.204	0.028	0.433	0.705
Proportion pine within 250 m buffer	13.195	6.256	2.109	0.035	0.326	0.661
Distance to nearest pine-dominated area	-0.007	0.003	-2.416	0.016	0.233	0.609

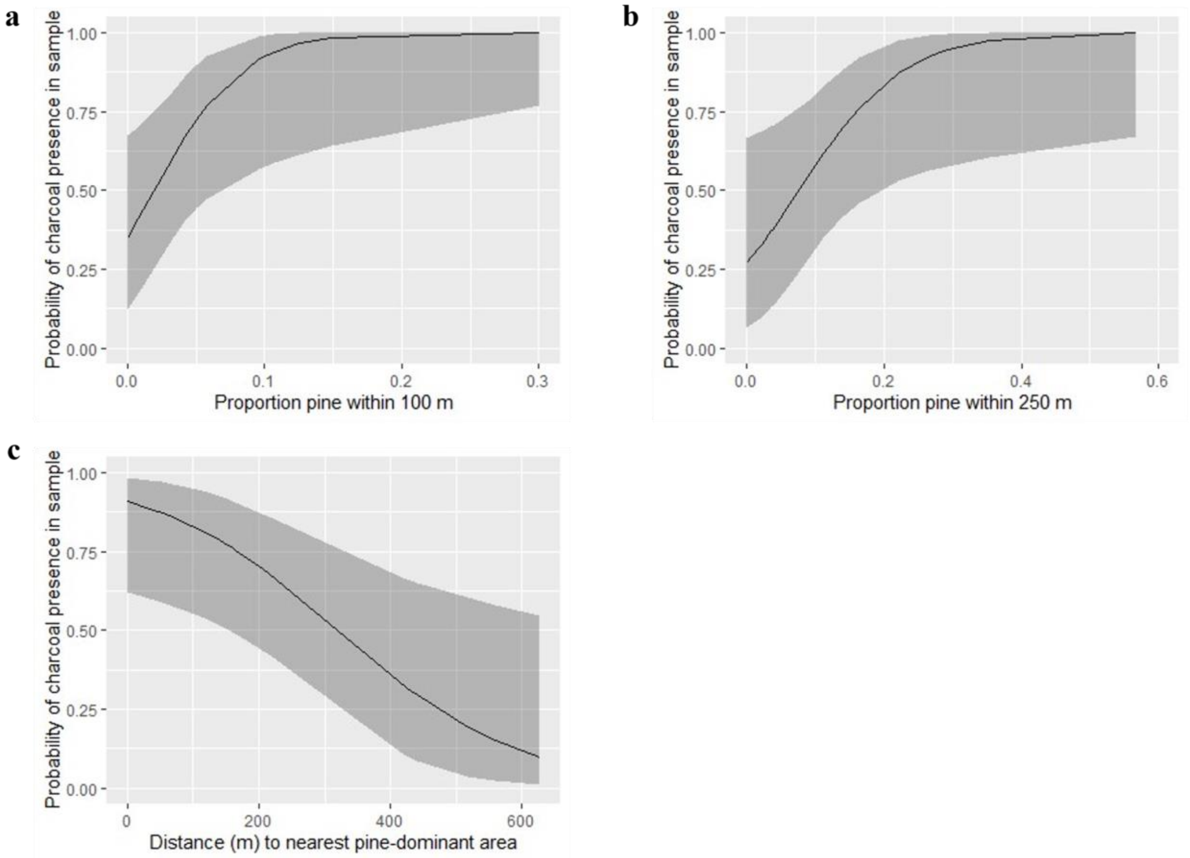

Figure 7. Model predictions (with 95% confidence interval) for probability of charcoal presence based upon **a.)** proportion pine within 100 m buffer, **b.)** proportion pine within 250 m buffer, and **c.)** distance to nearest pine-dominated area as fixed effects.

Because the only predictor variables identified as significant (for either charcoal amount or charcoal presence) all corresponded to the prevalence of pine in the surrounding area, they were clearly collinear with one another and could not reasonably be included as separate fixed effects in multivariate models. Therefore, my modeling exercise terminated at this point.

4. Discussion

4.1 The soil charcoal pool in comparison to past results

My first hypothesis was that the mean charcoal content in the project area would be in the range of 100-200 g/m^2 (as suggested by Ohlson and Tryterud (2000)), and would also exhibit substantial variability both regionally and locally. The observed project-wide mean of 168 (± 36) g/m^2 was in line with this expectation. This finding can be compared to other past results on soil charcoal in the same region; for example, Ohlson et al. (2013) found a very similar mean of 179 ± 27 g/m^2 in their study of a watershed located slightly southwest of this project's study area (approximately 60 km from this study's Blåfjell site). Likewise, in a study of spruce and beech stands in the same region (approximately 70 km from Blåfjell), Ohlson et al. (2017) found a mean of 162 ± 44 g/m^2. In a study of spruce and pine sites in the Trillemarka-Rollagsfjell nature reserve (about 30 km southwest of this study's Storås site), Kasin et al. (2017) found a slightly higher mean charcoal content of 269 ± 40 g/m^2, but for their spruce sites in particular a slightly lower mean of 230 ± 51 g/m^2 still overlapped with this study (in terms of their standard errors). These comparisons would seem to suggest that, despite high regional and local variability, overall estimates of the typical soil charcoal content in the forests of southeast Norway are reasonably reliable (and in turn, that estimates of the carbon stock associated with the soil charcoal pool in this region are likewise reliable).

However, although the overall charcoal mean of this study aligned with past results, the extent of the soil charcoal pool's variability must be emphasized. This study has very high standard errors associated with its mean estimates for single plots (Table 2), reflecting the patchiness of charcoal distribution at very small scales. This is due not only to wide variation in the charcoal amounts found in samples that had charcoal present, but also to the fact that even samples with no charcoal whatsoever were located in close proximity to samples with extremely high charcoal content (see the results from, e.g., Skotjernfjell NN and Braskereidfoss CC in Figure 4 and Table 2). The high variability found here also accords with past results in the region; for example Ohlson et al. (2013) (mentioned above) noted that despite taking hundreds of soil samples in a single watershed, their watershed-level mean estimate nonetheless had a wide standard error (indeed, not much smaller than the standard error for broader regional-scale estimates like that of this study). They also found that charcoal content could differ by as much as two orders of magnitude (34 to 1646 g/m^2) over a distance of only 10 cm, which accords with the major within-plot sample differences observed here. This extreme patchiness of soil charcoal even at the plot level shows that intensive sampling is an essential prerequisite for estimating boreal soil charcoal stocks with any precision, at all scales. This also bears upon the comparison of this study's paired plots (discussed in Section 4.2 below), insofar as the six soil samples taken per plot were too few to provide much precision in plot-level mean estimates.

In addition to comparing this study's overall mean and variability to past studies in the region, the size of the charcoal pool at two particular sites can be individually compared with very-nearby results from previous work: Ohlson et al. (2011) also analyzed soil charcoal at Gullenhaugen and Skotjernfjell. In two peat cores from each site, they found that charcoal was either entirely absent, or ceased accumulating shortly after local spruce establishment (Ohlson et al., 2011, supplementary information). The present study's finding that charcoal was completely absent at both Gullenhaugen plots accords with those previous results for the site. In general, caution must be taken in inferring an absence of historical fires from the absence of charcoal particles in particular soil samples (Ohlson & Tryterud, 2000), but in this case the combined evidence at least supports (though does not conclusively prove) the idea that the Gullenhaugen site has been a fire-free refugia at least since the time of local spruce establishment. At Skotjernfjell, however, this study's results differ from the previous findings: here charcoal was found at both plots for the site, and the species composition of identified charcoal pieces was 100% spruce (Figure 6), clearly showing that significant fire impacts have continued after spruce establishment at these plots. This implies a local mosaic distribution of fire-impacted versus fire-free spruce stands, as this study's Skotjernfjell plots were around 1 km away from the earlier study's location.

Lastly, there is also a more general discrepancy between the charcoal species compositions found by this study and the compositions identified in previous work in the region. Here, spruce charcoal was dominant at 13 of the 18 plots where charcoal occurred (Figure 6). This contrasts with Ohlson et al. (2017) and Kasin et al. (2017) (both mentioned above), who found that pine charcoal was strongly dominant even at spruce forest sites, which is taken to reflect fires in the historic pine forest prior to spruce establishment (and a subsequent decline in fire impacts after spruce arrived). It seems likely that this discrepancy is related to the fact that the EcoForest project plots used in this study are necessarily located on productive, drought-resistant sites (i.e., sites that are attractive for production forestry, in keeping with the project's main goal of studying management effects): spruce may have colonized such sites relatively early historically, and therefore may have been present on-site for a longer period during which occasional fires could still occur despite the general tendency of spruce to modulate the fire regime. Such ongoing fires at these spruce sites could also have been facilitated by anthropogenic activity, because it is known that fire frequencies in this region increased in correlation with human activity in the 17th and 18th centuries (Rolstad et al., 2017; Storaunet et al., 2013).

4.2 Site history of paired plots

Because this study's site pairs were intentionally selected to be as similar as possible, my second hypothesis was that there would be no significant difference in mean charcoal amount or charcoal species composition between CC and NN plots (either overall or for individual site pairs), reflecting generally equivalent historic fire regimes for each pair. For the most part my results supported this expectation, with no significant difference in charcoal content between CC and NN plots overall, and with seven of the 10 individual sites likewise showing no significant difference between their paired plots (Table 3). The paired plots also generally had similar charcoal species compositions (Figure 6). However, three particular sites did show a statistically significant difference in charcoal content between their CC and NN plots; these sites warrant particular attention in the context of validating the EcoForest site pair selection and are discussed individually below. Before beginning this discussion, it is worth emphasizing (as noted in the previous section) that the plot mean estimates are very imprecise due to the high degree of within-plot variation in charcoal content, and also that the mean estimates are often highly outlier-driven (Figure 4); in some cases the median charcoal content is very similar for paired plots despite drastically different plot means (Table 2). This makes it difficult to reach confident conclusions about differences in the size of the charcoal pool between the paired plots. Accordingly, this study's site-level statistical results should be viewed as indicative but not conclusive regarding differences in average charcoal content between the paired plots.

4.2.1 Differences at Storås

At the Storås site, the NN plot had significantly higher charcoal content than the CC plot (Table 3), and also had charcoal present in five of its six samples whereas the CC plot had charcoal in only one sample (Figure 4, Table 2). This could suggest that the NN plot has been significantly more fire-impacted, but two considerations further complicate any such conclusion: the steep topography at Storås, and the observed presence of an ash layer in the soil of the CC plot.

First, regarding topography, the terrain surrounding the Storås plots is the steepest among all this project's study plots. Such terrain can be expected to increase erosive transport of fresh charcoal particles during rain events (Major et al., 2010; Rumpel et al., 2006). Accordingly, Ohlson et al. (2017) noted that rugged terrain further increases the already-patchy nature of the soil charcoal pool. Essentially, the tendency of charcoal particles to form hot spots in local depressions and slope bottoms (Kasin et al., 2017) can be expected to be magnified in steep and rugged settings like those of the Storås plots. It is thus unsurprising that the observed mean difference between the Storås plots is especially driven by one high sample value (i.e., a major hot spot) at the NN plot (Figure 4); by contrast, the median charcoal content is low for both plots (Table 2). It is plausible that more intensive sampling might strike analogous hot spots at the CC plot too, eliminating the apparent difference in mean charcoal content between the two.

Second, I observed (both in the field and during laboratory analysis) a distinct ash layer in one of the samples from the CC plot--and despite the presence of ash, this sample did not contain any macroscopic charcoal. Ash is the result of high-intensity fire that completely consumes its organic fuel (Santín et al., 2012), thus its presence at the CC plot clearly indicates that the plot has been subject to fire in the past despite its relative scarcity of soil charcoal. This, too, accords with the steep topography at Storås, insofar as steep slopes are associated with faster-spreading, more-intense fires (Bountzouklis et al., 2022), and intense fires are conducive to ash production. A related further consideration is that many past studies have suggested that charcoal from prior fires can itself be consumed by subsequent intense fires (Czimczik et al., 2005; DeLuca & Boisvenue, 2012; Ohlson & Tryterud, 2000). If this is the case, the fires that resulted in ash deposition at the CC plot may also have substantially destroyed a soil charcoal record that was previously present. Other studies, however, have contested the extent to which significant charcoal mass can be lost to consumption by subsequent fires (Saiz et al., 2014; Santín et al., 2013). In any case, although the magnitude of possible charcoal loss by this mechanism is contested, the presence of ash at the CC plot at very least shows that the plot has definitely been impacted by fire to a greater extent than would be inferred from macroscopic charcoal alone.

In sum, the observed difference in mean charcoal content between the two Storås plots does not offer sufficient evidence to reach clear conclusions about possible differences in their site histories. Additionally, the apparent difference in charcoal species composition for the two plots (Figure 6) is misleading, because only a single piece of charcoal from the CC plot could be identified by Vedlab--and thus all it really shows is simply that pine charcoal is present at both plots (i.e., quantitative comparison is not possible). In light of the further complexities raised by steep topography and the potential re-consumption of earlier charcoal by intense ashproducing fires, further study would be required at the Storås plots in order to confidently support or challenge the similarity of their site histories.

4.2.2 Differences at Särkilampi

At the Särkilampi site, the NN plot had significantly higher charcoal content than the CC plot (Table 3), and also had charcoal in all six of its samples versus only three samples at the CC plot (Figure 4, Table 2). The observed difference between the paired plots here could potentially be explained by the two stands having diverging fire histories after local spruce establishment. This interpretation is consonant with this study's modeling result that charcoal occurrence is positively related to the prevalence of pine in the surrounding area (see Section 3.3 above), as well as with differences in the charcoal species composition at the two plots.

The NN plot is located in closer proximity to pine-dominated forest than the CC plot (approximately 50 m and 150 m, respectively), according to the SR16 geospatial data used in this study. The NN plot is also one of the only two plots in the whole study with a pine tree currently present inside the plot itself. This in turn implies that the NN plot is more proximate to a more intense fire regime, as can be expected in the nearby pine forest (Engelmark, 1987; Ohlson et al., 2011; Zackrisson, 1977). But because the nearest pine-dominant area is still over 50 m away from the NN plot, it is unlikely that the higher charcoal content at the plot is due to wind transport from fires in the nearby pine forest: wind could plausibly transport small amounts of microscopic charcoal into the plot, but not the high amount of macroscopic charcoal observed (Pitkänen et al., 2003; Sass & Kloss, 2015). Rather, it is clear that the high charcoal content at the NN plot reflects the fire history on-site--especially because in the sample with the highest charcoal content, I observed a large, intact piece of partly-burned wood, whose charcoal was identified as pine by the species analysis; this charcoal unambiguously originated from on-site vegetation. Further, although pine charcoal was dominant at both plots, its proportion was lower at the NN plot, with spruce charcoal also constituting a substantial proportion (31%) (Figure 6). This shows that the local spruce forest (and not just the previous and/or nearby pine) has been directly impacted by fire. By contrast, only a single piece of spruce charcoal was identified from the CC plot.

Taken together, this evidence suggests that the NN plot may have a higher mean charcoal content and a higher fraction of spruce charcoal because it continued to experience periodic fire after local spruce establishment. The CC plot may instead have experienced a decline in fire frequency after spruce establishment, as reflected by its scarcity of spruce charcoal. If so, this diverging fire history may have been driven by the NN plot's closer proximity to pine forest (and indeed, pine admixture within the stand), facilitating ongoing fires at the NN plot despite the local dominance of spruce. The plausibility of this interpretation is supported by previous results indicating that different spruce stands may experience different fire frequencies even when located quite near one another, as is suggested for the paired plots here (Wallenius, 2002), and that moist spruce sites can avoid fire even when nearby dry forest burns, as is suggested for the CC plot here (Wallenius et al., 2004). Further, Bråthen (2016) examined fire history at a site in the pine forest approximately 400 m west of the NN plot and found that fires occurred at least once per half century throughout the period 1550-1900 (with an especially high frequency in the early 19th century), which demonstrates that the NN plot was in close proximity not just to pine forest, but also to known fire events in that forest.

However, it should be noted that the evidence for this interpretation is at most suggestive and circumstantial (the matter could potentially be investigated further by dating charcoal particles from the two plots). Given the high within-plot variability of charcoal content in general, and the fact that the statistical difference between the two plots is driven by one particularly high sample value (i.e., a hot spot) at the NN plot (Figure 4), it cannot be ruled out that--contrary to the speculative explanation offered above--the apparent difference in charcoal content between the Särkilampi plots is simply an artifact of the high fine-scale patchiness of the charcoal pool, and that more intensive sampling at both plots would eliminate the apparent discrepancy between their estimated mean charcoal stocks.

4.2.3 Differences at Tretjerna

The site pair at Tretjerna showed the most marked difference of all in this study. The CC plot had significantly higher mean charcoal content than the NN plot, and this discrepancy was greater than that between any other site pair (Figure 4, Table 3). Additionally, unlike Storås and Särkilampi, the difference at Tretjerna was not outlier-driven, i.e., the difference between the plots remains statistically significant even if the highest single sample is omitted. Charcoal also occurred more frequently at the CC plot, which had charcoal particles present in all six of its samples, versus only two samples at the NN plot (Table 2). Further, the charcoal species composition was notably different at the two plots (Figure 6): although spruce was dominant at both, the CC plot also had a substantial proportion (38%) of willow charcoal, while only spruce charcoal was identified from the NN plot. The willow charcoal was also dispersed throughout four different samples, rather than being isolated to a single willow hot spot. It is difficult to account for these observed differences.

One possibly-relevant observation is that charcoal occurred very near the soil surface at the CC plot. Typically, charcoal in the upper organic soil can be taken to indicate relatively recent fire impact, while charcoal incorporated into the organic-mineral interface is from older fire events (Soucémarianadin et al., 2015). This would suggest that the CC plot at Tretjerna has been impacted by fire more recently than most of the other study plots. Also, the organic soil layer in samples from both Tretjerna plots was extremely shallow in general (often as little as 1 cm), which could be a further indication of recent fire: intense fires can consume the organic layer (Dyrness & Norum, 1983; Kane et al., 2007), and if this occurred recently, only a small amount of new organic soil would have accumulated subsequently. However, this observation alone clearly cannot explain the difference between the plots, because the NN plot (not only the CC) also had a very shallow organic layer.

It is also worth noting, regarding the substantial presence of willow charcoal at the CC plot, that willow is typically an early-successional species following disturbance (Segerström et al., 2008; Stocks et al., 2001), and has a relatively short maximum lifespan. The substantial amount of willow charcoal might therefore indicate that the CC plot has experienced (at least at some point in its history) a fire frequency that is unusually high for spruce forest, with fire returning to the stand while willow trees were still present following a relatively-recent previous disturbance. In light of the shallow organic layer at both plots, a plausible scenario is that they both experienced relatively-recent intense fires, while the CC plot alone experienced an even more recent, more moderate (i.e., charcoal-producing) fire.

These suggestions of unusually high fire frequency and relatively-recent fire are speculative at best. But in any case, given the uniquely stark contrast between the observed charcoal pools at these two plots, it seems unlikely that more intensive sampling would eliminate the apparent difference between them. Insofar as the EcoForest project relies on the general similarity of the paired plots, more study is warranted in order to better understand the possibly-divergent site histories at Tretjerna.

4.2.4 Other remarks

The high within-plot charcoal variability observed in this study could cut both ways: just as more intensive sampling could plausibly eliminate the apparent differences between plot means in some cases (as discussed above), it could alternatively reinforce plot differences that did not rise to the level of statistical significance in this study. This is particularly worth considering for the Skotjernfjell and Øytjern site pairs, both of which had an above-average charcoal mean at the NN plot and a very low charcoal mean at the CC plot (Figure 4), although those differences were not significant (Table 3). Four of the project's seven failed soil samples occurred at these sites, which further weakens the statistical analysis. However, unlike the sites discussed above, the paired plots at Skotjernfjell and Øytjern did not have notable differences in their proportions of samples with charcoal present (Table 2) or their charcoal species compositions (Figure 6). The differences in their charcoal means are also strongly outlier-driven, to such an extent that for both sites, if the highest single sample were omitted the mean estimate would then be higher at the CC plot rather than the NN plot (i.e., a reversal). The plot medians, by contrast, are very similar for both sites. I therefore suspect that within-plot variability and hot spots sufficiently explain the different means at these two site pairs (in keeping with the lack of statistical significance); it seems unlikely that more intensive sampling would uncover divergent site histories that were missed by this study.

On a final note, the observed absence of a systematic difference in charcoal content between CC and NN plots should not be taken to implicitly suggest that the practice of clear-cutting has no significance for the soil charcoal pool. In a broader perspective, management for modern production forestry in this region is associated with fire suppression (Rolstad et al., 2017; Storaunet et al., 2013), which of course necessarily inhibits the production and deposition of new pyrogenic charcoal. These considerations are beyond the scope of the current study, but Thiffault et al. (2008), for example, have reported on implications for soil chemistry and nutrient availability--including with respect to aromatic black carbon in particular--for clear-cut versus wildfire-affected boreal forest plots.

4.3 Outcomes from modeling the soil charcoal pool

My third hypothesis was that metrics of climate, terrain, and/or contemporary forest characteristics would be predictive of the amount and/or occurrence of macroscopic soil charcoal. For the majority of the examined variables, this hypothesis was not supported; the soil charcoal pool had no significant relationships with any of the examined climate or terrain metrics nor with most of the contemporary forest metrics. It is likely that for many of these variables, the lack of observed relationships is due to issues of scale, i.e., the soil charcoal pool turned out to exhibit extreme variability on a scale smaller than the resolution at which the tested variables were measured.

4.3.1 Climate and terrain variables

I expected to find a relationship between the charcoal pool and climate metrics because climate is one of the major controls on fire regimes (Glückler et al., 2021; McLauchlan et al., 2020). In brief, warmer and drier regions can be expected to be more fire-impacted than cooler and wetter ones. Accordingly, I tested for relationships with temperature, precipitation, and proximity to the coast (as a proxy for climate oceanity).

I expected to find a relationship with terrain metrics because terrain factors exercise control over all aspects of charcoal production (via fire occurrence and behavior), deposition, and transport (e.g., Kane et al., 2010; MacDonald et al., 1991; Zackrisson, 1977). Accordingly, I tested for relationships with terrain curvature, slope, and indices that reflect ruggedness and terrain-derived moisture/groundwater levels. I also tested for a relationship with heat load index because I expected that this metric might quantitatively reflect the tendency of fires to burn on south-facing slopes (i.e., greater insolation for southern aspects).

Ultimately, there were no correlations between the charcoal pool and any of the tested climate and terrain metrics. The tested relationships had no explanatory power (i.e., extremely low R^2 values) and lacked statistical significance (Appendix Tables A-1 and A-2). As noted above, the scale of analysis is likely responsible for this: most of the climate and terrain metrics were at 100 m scale, whereas charcoal content varied radically within 15 m × 15 m plots. Had within-plot charcoal content exhibited less variation, these metrics might have correlated with between-plot differences in the charcoal pool, but that was not the case. These results should not be taken to dispute the extensive previous findings on climate and terrain influences on charcoal stocks, but rather should be taken to emphasize that the relevant scale of influence is extremely fine-scale. This accords with previous recognition of the importance of micro-scale topography (e.g., Gale & Thomas, 2021; Kane et al., 2010), as well as with recent results from Haukenes et al. (2022) who found that plot-level (in this case, sub-meter) slope is more important than general terrain slope in determining soil carbon stocks. Apart from these considerations of scale, it is also possible that secondary transport (e.g., soil disturbance and erosive processes relocating previously-deposited charcoal) has to some extent weakened the relationships between charcoal distribution and local fire conditions (as reflected by climate/terrain metrics) over time (Ohlson et al., 2013).

The absence of relationships between the charcoal pool and climate/terrain variables in this study contrasts with Ahmed et al. (2017), who modeled pyrogenic carbon stocks in the western United States and found significant relationships with mean annual temperature, mean annual precipitation, and slope (as well as other variables not examined in this study). Further, scale issues do not account for this discrepancy, because they used terrain data at 90 m resolution, which is similar to the 100 m resolution of the variables tested here. The clear difference, instead, is that they modeled charcoal stocks in a very large area encompassing multiple drastically different ecosystems (i.e., forests, grasslands, croplands, and others); indeed, the relationships they found with temperature and precipitation are in the opposite direction as would be expected within forests specifically. This suggests that modeling soil charcoal with terrain and climate data at 100 m (or similar) resolution is possible, but may only be relevant for rough estimation of charcoal stocks at very broad, sub-continental scales, rather than the regional (and forest-specific) scale of this study.

4.3.2 Contemporary forest characteristic variables

I expected that contemporary forest characteristics (species composition, site index, and/or density) might be predictive of charcoal stocks because vegetation type and structure are known to determine fuel loads and influence the fire regime. Regarding species composition, it is well-established (as discussed previously) that pine forests typically experience a more frequent and more intense fire regime than spruce forests, and that spruce establishment exerts influence on the fire regime independently of climate (Ohlson et al., 2011). Site index might also be correlated with the fire regime: Simard et al. (2007) have suggested that boreal forest productivity may sensitively reflect differences in fire regime at the landscape scale. Finally, density may reflect past fuel conditions: Ohlson et al. (2013) identified a positive relationship between contemporary forest density and charcoal stocks, which implies that current forest density reflects the past density of combusted biomass (although subsequent results have conflicted, with Kasin et al. (2017) finding no such relationship). I therefore expected that, insofar as contemporary species composition, site index, and density can be indicative of historic forest conditions and fire regimes, they might be predictive of soil charcoal stocks at the study plots. I examined these variables in surrounding buffers of varying sizes in order to explore the typical scale of dependence, and also because this study's sites were all relatively high-productivity spruce stands by design, which constrained the extent to which these variables might vary immediately on-site.

The only aspect of contemporary forest conditions that had any significant relationship with the charcoal pool was the prevalence of pine in the surrounding area. The relationship between pine prevalence and charcoal amount was only minor in its explanatory power (Table 4), suggesting that the amount of charcoal in a given soil sample is more directly controlled by local particularities of fuel loads and deposition hot spots. But pine prevalence's positive relationship with the likelihood of charcoal presence (as a binary) was more substantial (Table 5, Figure 7), suggesting that patterns in charcoal presence/absence are substantially influenced by species composition in the surrounding area insofar as it reflects historic fire regimes. In light of the previous section's discussion of scale issues with respect to the absence of relationships between the charcoal pool and climate or terrain variables, it is notable that contemporary species proportions on an analogous scale (i.e., pine proportion summarized within the surrounding 100 m buffer) nonetheless had significant explanatory power for charcoal occurrence. This might suggest that the control of forest composition on fire regime (*sensu* Ohlson et al., 2011) is evident not only at the immediate stand level, but also at a slightly-broader landscape scale--i.e., that although all the specific plots in this study are locally spruce-dominated, differences in their historic fire regimes may have been significantly influenced by the prevailing species composition in their broader surroundings on the scale of hundreds of meters, and not just by the characteristics of the spruce stand on-site.

The evidence provided by this study does not allow clear identification of a single narrative regarding fire history as it relates to surrounding pine prevalence. One plausible scenario is that a high proportion of pine nearby encourages ongoing periodic fires on-site even after local spruce establishment; another scenario is that a high proportion of pine nearby indicates that spruce colonization (and associated reduction of fire) occurred on-site only in relatively recent history. Clearly neither scenario is universally applicable here, because the study plots with high charcoal presence did not have uniform charcoal species compositions (Figure 5, Figure 6): in some cases spruce charcoal was dominant, which would accord with the first scenario, insofar as spruce charcoal indicates ongoing fire after spruce establishment. On the other hand, in some cases pine charcoal was dominant and spruce charcoal was minimal or absent, which would accord with the second scenario, insofar as absence of spruce charcoal implies absence of fire after spruce establishment.

The observed relationship between the charcoal pool and surrounding pine prevalence might also partly account for the absence of relationships with the other tested forest variables, i.e., the influence of surrounding species composition could confound or override subsidiary relationships with density or site index. It is possible that such relationships would be found in a study that first grouped its sites according to surrounding species proportions, and then examined those groups separately for relationships with density or site index. But it is also possible that such relationships are not just obscured, but simply absent: Kasin et al. (2017) have suggested mechanisms by which human land management may have dissociated contemporary density from historic density/fuel loads, for instance.

5. Conclusions

While this project's overall mean soil charcoal content aligns with the findings of past studies in southeast Norway, its very high within-plot variability and strong influence from individual high-charcoal "hot spots" underscore the necessity of conducting intensive sampling in order to characterize soil charcoal stocks with any precision, even at the small scale of the 15 m × 15 m plots studied here. This inherent variability complicates inferences about comparative site histories based upon differences in the size and composition of the charcoal pool, even for sites that are otherwise very similar by design (i.e., this project's paired spruce forest plots). As seen in the investigation of the paired plots here, differences in the size of the soil charcoal pool at the stand level may implicate very different factors, such as terrain and erosive/depositional processes in the case of Storås, or modulation of the fire regime by surrounding species composition in the case of Särkilampi--but given the imprecision of the plot-level estimates, such inferences remain suggestive rather than conclusive. Thus it is clear that while the presence of macroscopic charcoal definitively indicates local impact from historic fires, a broader suite of evidence (e.g., carbon dating, dendrochronology) must be incorporated in order to reach more detailed conclusions about site history.

Similarly, the small-scale variability of the soil charcoal pool complicates efforts to model its relationships with relevant environmental variables. Here, there were no correlations whatsoever between soil charcoal content and climate or terrain metrics, despite strong theoretical reasons to expect such relationships. This is likely because the examined metrics were too coarse in resolution (100 m) to account for within-plot variation. To be successful, such modeling efforts would likely need to rely on explanatory variables measured at finer (i.e., sub-meter) scales. Practically speaking, this suggests that field measurements are a necessity; remotely-sensed datasets at national or regional scales may be of limited utility for this purpose.

In light of the above, it is interesting that this project nonetheless identified a positive relationship between soil charcoal occurrence and surrounding species composition at relatively coarse scales (i.e., within buffers of 100 m and 250 m radius): although the *amount* of soil charcoal is primarily controlled by fine-scale factors, its relative *presence* significantly depends upon the composition of the broader landscape. Insofar as species composition is known to influence stand-level fire regimes independently of climate, this may suggest that landscape-level composition (not just stand-level composition) is also a relevant influence. Further work could investigate whether this relationship with surrounding species composition holds for sites more diverse than the high-productivity spruce plots examined here.

6. References

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Appendix

1. Supplemental tables and figures

Table A-1. Complete results from mixed effects linear regression models of logarithmically transformed charcoal amount. Plot and site (nested) are random effects in all models. The only significant results are those duplicated in Table 4 of the main text (proportion pine within 100 m and 250 m; distance to nearest pine-dominated area).

Predictor	Estimate	SE	t-value	p	Marg. R^2	Cond. R^2
Mean annual temperature	0.176	0.363	0.484	0.641	0.008	0.432
Annual precipitation	-0.004	0.004	-0.855	0.417	0.025	0.429
Proximity to coast	0.008	0.011	0.722	0.491	0.018	0.430
Terrain curvature (positive vs. negative)	1.540	0.733	2.101	0.066	0.065	0.503
Slope	4.659	5.975	0.780	0.447	0.017	0.429
Vertical distance to channel network	0.002	0.007	0.286	0.778	0.002	0.432
Topographic wetness index	-0.193	0.242	-0.800	0.435	0.011	0.429
Terrain ruggedness index	0.059	0.081	0.733	0.473	0.015	0.430
Heat load index	1.068	16.356	0.065	0.949	<0.001	0.430
Proportion non-spruce at plot	2.132	3.853	0.553	0.588	0.006	0.428
Forest density at plot	-0.018	0.046	-0.386	0.705	0.004	0.450
Proportion pine within 100 m buffer	11.133	5.189	2.146	0.045	0.091	0.405
Proportion pine within 250 m buffer	6.808	2.689	2.532	0.024	0.126	0.408
Proportion pine within 500 m buffer	4.867	2.431	2.002	0.077	0.085	0.413
Proportion pine within 1000 m buffer	4.819	2.252	2.140	0.061	0.096	0.412
Average site index within 100 m buffer	0.023	0.162	0.144	0.887	<0.001	0.427
Average site index within 250 m buffer	0.056	0.197	0.286	0.779	0.002	0.424
Average site index within 500 m buffer	0.247	0.234	1.054	0.312	0.033	0.422
Average site index within 1000 m buffer	0.258	0.266	0.973	0.354	0.030	0.423
Average density within 100 m buffer	0.041	0.056	0.730	0.478	0.016	0.420
Average density within 250 m buffer	0.021	0.070	0.303	0.766	0.003	0.422
Average density within 500 m buffer	0.064	0.090	0.718	0.483	0.015	0.423
Average density within 1000 m buffer	0.123	0.122	1.004	0.334	0.031	0.428
Distance to nearest pine-dominated area	-0.005	0.002	-2.517	0.030	0.130	0.413

Table A-2. Complete results from mixed effects logistic regression models of likelihood of charcoal presence. Plot and site (nested) are random effects in all models. The only significant results are those duplicated in Table 5 of the main text (proportion pine within 100 m and 250 m; distance to nearest pine-dominated area).

Predictor	Estimate	SE	z-value	p	Marg. R^2	Cond. R^2
Mean annual temperature	0.308	0.511	0.603	0.547	0.021	0.596
Annual precipitation	-0.347	0.630	-0.551	0.581	0.016	0.575
Proximity to coast	0.012	0.014	0.752	0.452	0.028	0.574
Terrain curvature (positive vs. negative)	1.414	0.959	1.475	0.140	0.048	0.614
Slope	6.842	7.990	0.856	0.392	0.032	0.590
Vertical distance to channel network	0.006	0.009	0.650	0.516	0.019	0.593
Topographic wetness index	0.072	0.372	0.194	0.846	0.001	0.583
Terrain ruggedness index	0.083	0.105	0.792	0.428	0.025	0.592
Heat load index	5.768	24.207	0.238	0.812	0.003	0.593
Proportion non-spruce at plot	4.159	4.698	0.885	0.376	0.021	0.574
Forest density at plot	-0.025	0.057	-0.432	0.666	0.006	0.599
Proportion pine within 100 m buffer	31.452	14.273	2.204	0.028	0.433	0.705
Proportion pine within 250 m buffer	13.195	6.256	2.109	0.035	0.326	0.661
Proportion pine within 500 m buffer	6.611	3.926	1.684	0.092	0.131	0.591
Proportion pine within 1000 m buffer	6.442	3.545	1.817	0.069	0.145	0.586
Average site index within 100 m buffer	-0.105	0.220	-0.477	0.633	0.010	0.594
Average site index within 250 m buffer	-0.071	0.281	-0.253	0.801	0.003	0.593
Average site index within 500 m buffer	0.187	0.314	0.597	0.551	0.017	0.581
Average site index within 1000 m buffer	0.180	0.363	0.497	0.619	0.013	0.582
Average density within 100 m buffer	0.018	0.075	0.232	0.816	0.002	0.582
Average density within 250 m buffer	-0.004	0.092	-0.047	0.962	<0.001	0.587
Average density within 500 m buffer	0.086	0.119	0.724	0.469	0.023	0.584
Average density within 1000 m buffer	0.188	0.178	1.056	0.291	0.059	0.607
Distance to nearest pine-dominated area	-0.007	0.003	-2.416	0.016	0.233	0.609

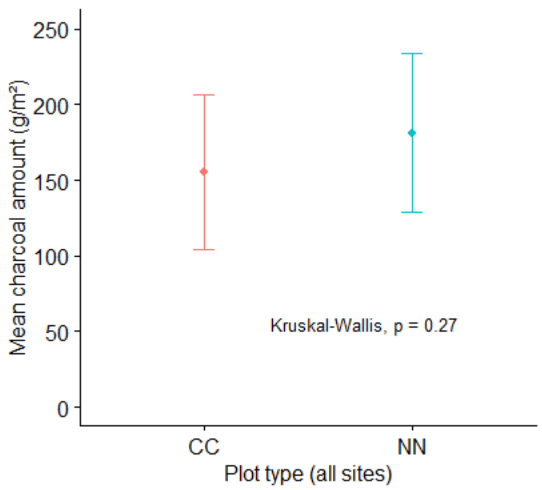

Figure A-1. Mean charcoal amount (± 1 SE) at CC plots and NN plots respectively, project-wide. The two plot types do not significantly differ. This figure provides an alternate visualization of information from Figure 4, Table 2, and Table 3 in the main text.

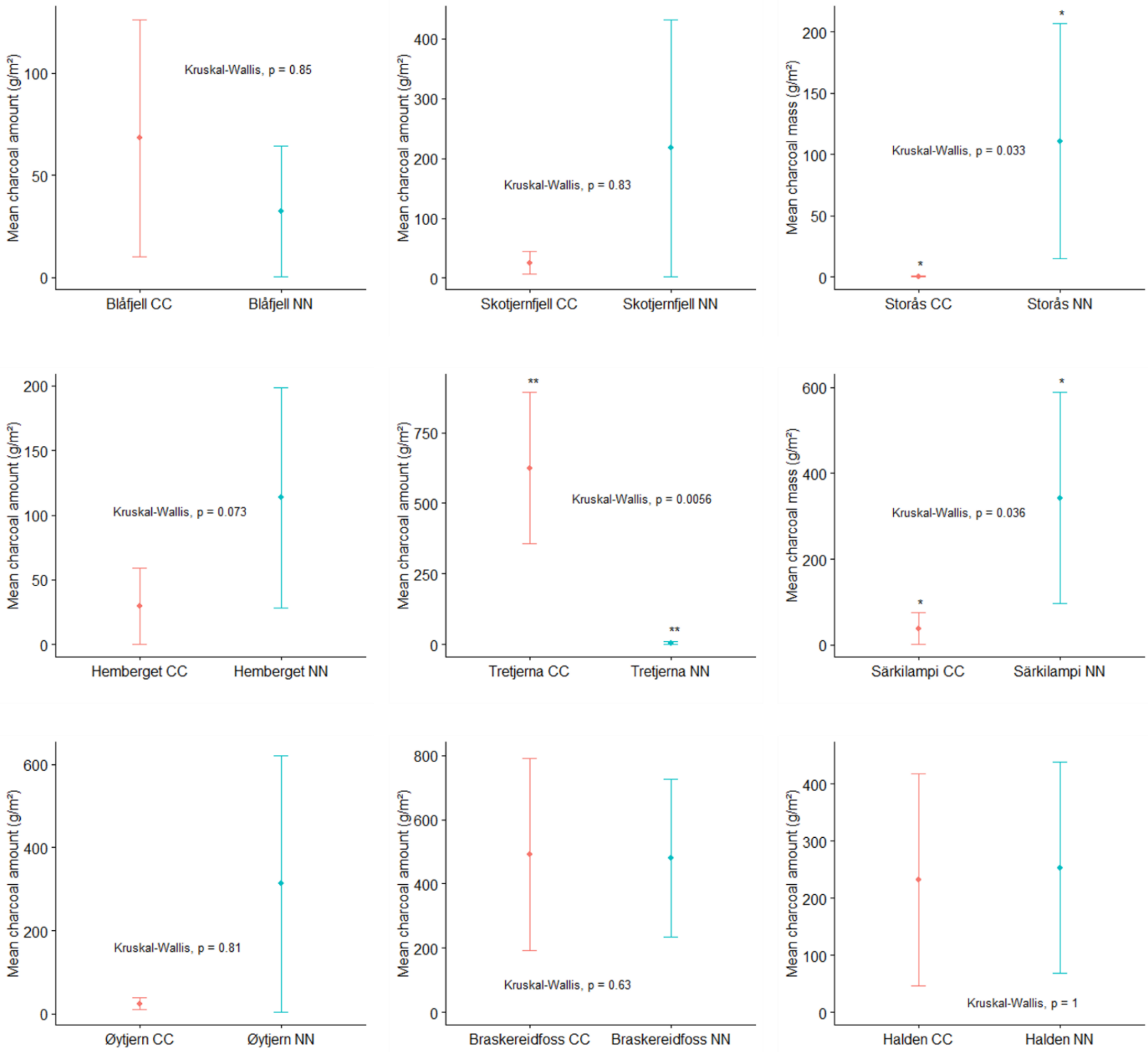

Figure A-2. Comparison of charcoal amount (mean ± 1 SE) for all individual sites where charcoal was present (i.e., Gullenhaugen is omitted). One asterisk (*) indicates significant difference between paired plots at 0.05 significance level; two asterisks (**) indicates significant difference between paired plots at 0.01 significance level (Kruskal-Wallis tests). This figure provides an alternate visualization of information from Figure 4, Table 2, and Table 3 in the main text.

2. Detailed GIS processing procedures

This section documents the complete ArcGIS 10.8.1 geoprocessing tools and settings used to calculate dominant species proportions, average forest density, average site index, distance to nearest pine-dominant area, and heat load index (as referenced in Section 2.4.2. of the main document).

- Data source for dominant species, forest density, and site index: NIBIO SR16 rasters for Innlandet and Viken Counties (coordinate system: ETRS1989, projection: UTM Zone 32N, resolution: 16 m)
    - https://www.nibio.no/tema/skog/kart-over-skogressurser/skogressurskart-sr16
- Data source for pine-dominant areas: vector version of SR16 (same source and coordinate system as raster version)
- Data source for heat load index: digital terrain model (DTM) from Kartverket (coordinate system: ETRS1989, projection: UTM Zone 33N, resolution: 1 m)
    - The relevant individual DTM scenes were obtained by submitting shapefiles of this project's plot locations to the export tool at https://hoydedata.no/
- In all procedures below, each buffer size (100 m, 250 m, 500 m, and 1000 m radius; and 15 m in the case of heat load index) was processed separately, and the buffers for CC and NN plots were processed separately. (If all buffers are included in a single dataset, raster processing errors occur in the areas where they overlap.)

Dominant species proportions

- Input: SR16 "SRRTRESLAG" rasters
- Combined the Innlandet and Viken rasters using the "Mosaic to New Raster" tool (pixel type: 16 bit unsigned; number of bands: 1)
- Used the "Reclassify" tool to assign value 0 (i.e., non-forest) to No Data areas
- For each buffer distance, used the "Zonal Histogram" tool to obtain cell counts for each dominant species type (spruce, pine, deciduous, or non-forest) within the buffer
    - Input feature zone: plot buffers. Zone field: plot number. Input value raster: combined treslag raster
- Joined the output tables to combine CC and NN for all buffer distances in a single table
- Exported the joined table into R to convert cell counts into proportions

Average forest density

- Input: SR16 "SRRGRFLATE" rasters
- Combined the Innlandet and Viken rasters using the "Mosaic to New Raster" tool (pixel type: 16 bit unsigned; number of bands: 3)
- For each buffer distance, used the "Zonal Statistics as Table" tool to calculate the average raster value within the buffer
    - Input feature zone: plot buffers. Zone field: plot number. Input value raster: Band 1 of the combined grflate raster. Ignore No Data in calculations: enabled. Statistics type: mean
- Joined the output tables to combine CC and NN for all buffer distances in a single table

Average site index

- The processing steps for site index are identical to those for forest density above, except that the input is the SR16 "SRRBONITET" raster (number of bands: 1).

Distance to nearest pine-dominant area

- Input: SR16 vector version
- Extracted pine-dominant polygons (treslagSammenstilt = 2) from the feature classes for both Innlandet and Viken
- Combined the pine-dominant polygons for Innlandet and Viken into a single feature class using the "Merge" tool
- Calculated the nearest distance from each plot to a pine-dominant polygon using the "Near" tool
    - Input features: plot points. Near features: combined pine-dominant polygons. Method: geodesic

Heat load index

- Input: DTM rasters
- Clipped the DTM rasters to 100 m buffers around the plots using the "Extract by Mask" tool (saves time in subsequent steps by processing only the relevant area, rather than the entire raster scenes)
- Used the "Heat Load Index" tool from the custom "Geomorphometry & Gradient Metrics" toolbox to generate heat load index rasters from each clipped DTM raster
- Combined the outputs for all plots using the "Mosaic to New Raster" tool (pixel type: 32 bit float, number of bands: 1)
- Used the "Zonal Statistics as Table" tool to calculate the average heat load index within the buffers
    - Input feature zone: plot buffers (15 m version). Zone field: plot number. Input value raster: the combined heat load index raster. Ignore No Data in calculations: enabled. Statistics type: mean

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway