BALTIC FORESTRY

http://www.balticforestry.mi.lt
ISSN 1392-1355
eISSN 2029-9230

Baltic Forestry 2021 27(1): 478
Category: research article
https://doi.org/10.46490/BF478

Forest soil charcoal and historical land use

PILLE TOMSON *, TANEL KAART AND KALEV SEPP

Estonian University of Life Sciences, Kreutzwaldi 1, Tartu 51006, Estonia

** Corresponding author:* pille.tomson@emu.ee

Tomson, P., Kaart, T. and Sepp, K. 2021. Forest soil charcoal and historical land use. *Baltic Forestry* 27(1): article id 478. https://doi.org/10.46490/BF478.

Received 26 March 2020 **Revised** 23 December 2020 **Accepted** 27 January 2021

Abstract

Charcoal deposits in forest soils have been considered mainly in the context of wildfires. However, slash-and-burn cultivation was widespread in Northern Europe until the beginning of the 20th century and extensive areas of former swiddens are now covered by forests. The study sites were in Karula National Park in Southern Estonia. Cadastral maps of the 19th century were used to identify the historical land use. Macroscopic (visible) charcoal was studied in 57 soil pits, located in historical slash-and-burn sites, forests, former arable fields, recent forest fire sites, and experimental slash-and-burn fields. The locations of charcoal in the soil profile were recorded. In four sites, the charcoal samples were dated. In regions where the swiddens were common in the 19th century, forest soil charcoal is widespread. The charcoal depth in the soil was related to agricultural land use duration and methods at different intensities. The depth of the charcoal-rich layer best reflected the historical cultivation, though patchy spatial distribution and the evident translocation of charcoal of different fire events complicate the interpretation of the charcoal pattern. At present time further studies should address soil charcoal origin and amount in the Baltic region.

Keywords: slash-and-burn cultivation, swidden, wildfire, land use history, soil charcoal, boreal forest

Introduction

From the perspective of climate change, it becomes more important to understand past fire regimes to predict ecosystem responses to these disturbances. Numerous authors have analysed microscopic charcoal in sediments of lakes and wetlands to detect fire frequencies; however, in this case, the exact locations of fires could not be determined. Visible charcoal fragments with a diameter of at least 1–2 mm have been described as macroscopic (Wallenius 2002, Scott 2010). Soil macroscopic charcoal is considered a sign of local burns (Carcaillet 1998, Ohlson and Tryterud 2000, Lynch et al. 2004) because it does not translocate through the air and, therefore, has been used to study the frequency of forest fires and historical species composition (Ludemann 2003, Ponomarenko et al. 2013, Robin and Nelle 2014, Robin et al. 2014, Kasin et al. 2017). Less attention has been paid to forest soil charcoal formed by slash-and-burn cultivation and land clearing. The effect of slash-and-burn cultivation on forest soils has recently received attention in the Baltic region (Tomson et al. 2018, Kukuļs et al. 2019).

Soil bioturbation, erosion, and freeze-thaw processes contribute to the burial of charcoal (Carcaillet 2001). Forest fires might consume the complete soil organic horizon and leave charcoal above the mineral horizon (Weimarck 1968, Ohlson and Tryterud 2000, Czimczik et al. 2005, Ohlson et al. 2009). If the fire is less intense, only part of the organic material might be destroyed, and charcoal might remain in the organic layer (Czimczik et al. 2005). Soil fauna and plant roots contribute to soil bioturbation and, therefore, to charcoal translocation (Gabet et al. 2003). In forests, the main factor burying charcoal is tree uprooting by windthrow (Gavin 2003, Talon et al. 2005, Bobrovsky 2010).

Slash-and-burn cultivation (swidden agriculture) has been widespread in Europe and continued into the 20th century at least in Austria, Germany, Sweden, Norway, Finland, Latvia, Estonia, and Russia (Sigaut 1979, Hamilton 1997, Bobrovsky 2010, Jääts et al. 2010). However, the effects and traces of slash-and-burn cultivation on soil have been little studied in Europe.

Presumably, slash-and-burn cultivation produced a lot of charcoal and mixed it into the soil. Traditionally, wooden harrows and primitive ards were used to cultivate the swiddens. The depth of ploughing with forked ards was 5–10 cm (Pärdi 1998). The ploughing depth increased at the same time as slash-and-burn cultivation declined and mouldboard ploughs were introduced. In Estonia, the ploughing depth was up to 15 cm at the beginning of the 20th century and increased to 20–25 cm after tractors were introduced in the 1950s (Kuum 1971).

Bobrovsky et al. (2019) found charcoal at 4–45 cm depths in Ryazan region in Russia. The charcoal was found mainly from old arable layers; the charcoal was scattered and located unevenly in light clusters or narrow layers.

Ponomarenko et al. (2019) registered 5–7 cm thick swidden layers and described uniformly distributed rounded charcoal fragments with a median diameter of 4–5 mm as characteristic of slash-and-burn cultivation at a documented swidden site in Estonia. Mechanical abrasion due to tillage is considered to rub and crush the charcoal (Ponomarenko and Anderson 2013, Bobrovsky et al. 2019); therefore, in fields that have been arable for a long time, only a small fraction of charcoal would be expected.

This study aims to test the links between forest soil charcoal location and land-use history, agricultural land-use duration and methods, and to discuss the pedoturbation mechanisms to obtain a better understanding of forest soil charcoal deposits. The main hypothesis was that the locations of macroscopic charcoal in forest soils due to land use duration and methods at different intensities (used tillage tools, cultivation duration) reflects agricultural land-use history.

Materials and methods

Study area

The study was carried out in Southern Estonia in Valga and Võru counties in Karula National Park (Figure 1). The climate is moderately continental here. The average temperature is –5°C in the winter and 16°C in the summer; annual precipitation is approximately 700 mm (Tarand et al. 2013). The soils are mainly sandy and loamy acidic soils covering Quaternary sediment moraines on the Devonian bedrock classified as *Albeluvisols, Luvisols* and *Podzols* (Kõlli 2012). The region is characterised mainly by a hilly relief with moraine kames and eskers. The relative height of the hills is 25–40 m, and the slopes reach up to 30°. In this region, the first signs of cereal cultivation are attributed to the Bronze Age (Poska et al. 2017).

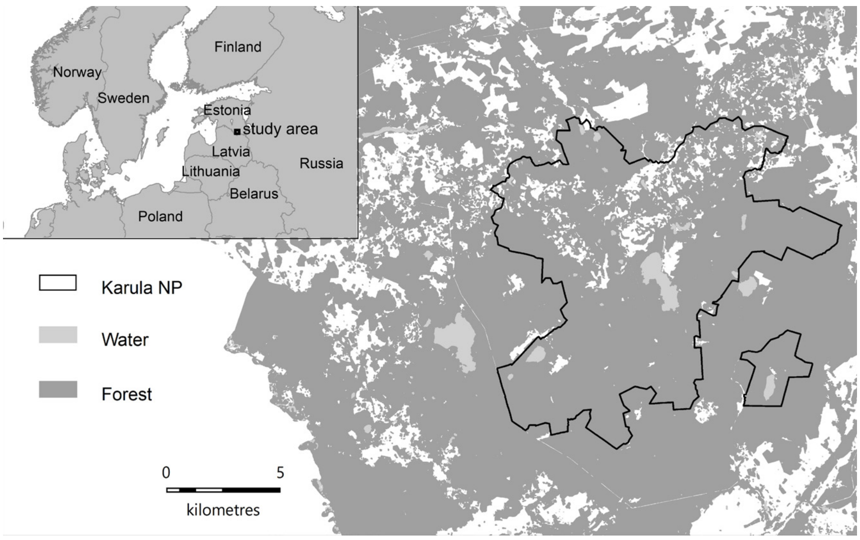

Figure 1. Location of the study area

Fieldwork

Study sites were selected using historical maps. Cadastral maps from the 19th century were utilised (Appendix 1) to identify land use of the 19th century. Permanent arable fields, forests, and *buschlands* were selected for soil sampling. *Buschlands* were areas used for rotational slash-and-burn cultivation during the 19th century (Jääts et al. 2010). Still, during fieldwork, terrace-like lynchets were found in three forest site past ploughings responsible for formation of these lynchets (Tomson et al. 2018).

Land use at the beginning of the 20th century was identified using one verst topographical map (published in 1912) (Estonian Land Board 2019) that reflected the land cover classes.

Soil pits were established in 57 sites with different land-use history in 2014–2017. Twenty-eight of the sites were former *buschlands*, of which 15 were mapped as forests and 13 as arable fields on one verst topographical map. The 13 arable field sites were afforested later in the 20th century. At locations mapped as forests in the 19th and early 20th centuries, the soil was sampled from 18 sites. Additionally, soil from four sites of historical forest in places where forest fires took place around 2006 was sampled. These recent forest fire sites were identified using the Management Plan of Karula National Park (Keskkonnaamet 2007). All these 50 study sites are covered by fresh and dry boreal forests (classification by Paal 1997). For comparison, five sites were selected that were depicted as permanent arable both in the 19th century and in 1912 and which are grasslands now. Additionally, two sites were sampled (four pits) in abandoned experimental slash-and-burn fields established in 2007 and 2009 by the Estonian National Museum; the experiment is described by Jääts et al. (2011). The experimental fields were established in long-time fallows of historical permanent arable fields and are currently covered by grasses and shoots of deciduous trees.

Luvisols were most common in arable fields, while former *buschland*s were dominated by *Haplic Albeluvisols* and less by *Albic Umbric Retisols* (*Stagnic Luvisols)*. Historical forest sites were dominated by *Haplic Albeluvisols* and less by *Podzols*. Fine sands and sandy loams dominated. All recent forest fire locations were in *Podzols*.

Soil pits (50 × 50 cm) were excavated as semi-excavations (Astover et al. 2013). The depth of pits depends on soil profile but ranged between 40 and 60 cm. Charcoal pieces visible in the soil profile and with a linear dimension greater than 0.1 cm were considered as macroscopic charcoal. To characterise the location of charcoal in the soil, the maximal and minimal depths of charcoal pieces in the profile were registered. The layer containing a higher portion of charcoal was visually assessed and upper and lower borders of this layer were measured. Hereinafter, this layer is referred to as the *charcoal-rich layer*, although it did not contain much charcoal in most places. In soil pits, the thicknesses of litter and humus layers were measured. In 34 observed sites (21 *buschlands* and 13 forests), the soil was sampled for chemical analyses (pH, N, C, soil specific surface area of humus layer) during a previous vegetation survey; differences were not found between these land-use groups, and this data has been published elsewhere (Tomson et al. 2018). Therefore, the chemical analyses were not the focus of the present study.

Data processing and datasets

To analyse the location of charcoal, three land-use groups were defined according to the land use types of the 19th century as follows: arable fields, *buschlands*, and forests. Four pits from two experimental slash-and-burn fields and recent forest fire sites were included into the dataset.

To examine the correlation between land-use duration and methods and charcoal location, six groups were defined with different land-use histories and cultivation durations: arable fields as most-modified by cultivation; former *buschland*s that were arable fields on the 1912 map; *buschland*s that were depicted as areas with single trees and bushes on the 1912 map; *buschland*s depicted as forests in 1912; sites depicted as forests in the 19th and 20th centuries but with lynchets in foot slopes that indicate cultivation; and the forests of the 19th and 20th century without traces of cultivation. These groups reflect both cultivation duration and land-use methods (long-term forest, slash and burn, or permanent arable cultivation) and form the series from most effected soils to presumably intact soils. The recent forest fire sites and experimental fields were excluded from this analysis.

The charcoal from two slash-and-burn sites and two forest sites was dated. The samples were collected from the humus layer and illuvial layer in *buschland* sites and from illuvial layer from the forest site. The samples were taken from the trench wall with a scoop and were stored in plastic Minigrip bags as required (BETA 2021). The conventional radiocarbon dating method was applied to the bigger charcoal samples (from forest sites) at the Radiocarbon Laboratory, the Institute of Geology at Tallinn University of Technology. For samples of less than 5 g, both from slash-and-burn cultivation sites, accelerator mass spectrometry was applied in Poznan Radiocarbon Laboratory. In both cases, the assemblages of different fragments from the same layer were dated. The calibration was done by the same laboratories using OxCal 4.3 program (Bronk Ramsey 2009, OxCal 2017).

All statistical analyses were performed with *R* 3.3.3 software package (R Core Team 2020), and the results were considered statistically significant at $p \leq 0.05$. The Kruskal-Wallis test was applied to compare the charcoal location characteristics in land-use groups. In the case of a statistically significant overall effect of land use, the pairwise comparison of land-use groups was performed with the Wilcoxon test followed by the Holm correction for multiple testing. The Spearman correlation analysis was used to study the relationships between charcoal location and land-use groups with different land-use history and cultivation durations.

Results

Macroscopic charcoal was found in 55 (96.5%) observed sites. Charcoal was not found in the two-former slash-and-burn cultivation sites.

The average minimal depth of charcoal did not differ between the historical land-use groups of arable fields (19.4 cm), *buschlands* (13.1 cm), and forests (10.8 cm) (Table 1). In the highest position, the charcoal located in the experimental slash-and-burn fields (2 cm on average) and recent forest fire locations (0.5 cm on average) did not differ between each other and between arable fields. The statistical test did not detect differences for most of the charcoal characteristics of arable, experimental slash-and-burn cultivation, and forest fire groups because of the small number of sites and great variability of characteristics.

In recent forest fire sites, some charcoal was found from the litter layer. In all other groups, including the experimental slash-and-burn fields, charcoal was not found above the mineral soil.

A comparison of the charcoal location in the mineral soil (according to the humus layer), considering that at the time of cultivation there was no litter layer in *buschland*s, revealed that the minimal and maximum depths of charcoal were different in arable fields (19.4 and 35.4 cm) and forests (4.7 and 14.8 cm), while in *buschlands* the depths (8.6 and 19.9 cm) were between fields and forests and neither different from them (Table 1). The highest position in mineral soil was associated with recent forest fires (- 3.75 cm on average) where charcoal was also found in the litter layer. For arable fields and experimental slash-and-burn patches, the average values were the same as the absolute depths because the forest litter layer is missing from these sites.

The average maximum depths of charcoal were ranked as former arable fields (35.4 cm), then in *buschlands* (24.7 cm) and forests (20.8 cm) and were not statistically different from each other. The pattern was similar according to mineral soil, but the difference between arable fields and forests was confirmed in this case. Single pieces with a diameter of 1–2 mm were found under the humus layer in all land-use types.

In the *buschland* and forest, the average depths of the upper border of the charcoal-rich layer were in similar positions (13.8 and 10.8 cm, respectively) but it was deeper than in arable fields (28.2 cm) (Table 1). The lower border of the charcoal-rich layer differed in arable fields

Table 1. Average values (with standard deviations in brackets) of charcoal location characteristics in soil depending on land-use history

Characteristics, cm	Land use in the 19th century			E (n = 4)	W (n = 4)	*P*-value
	A (n = 5)	B (n = 28)	F (n = 16)			
Minimal depth of charcoal	19.4 (10.2)[ab]	13.1 (5.85)[a]	10.8 (3.89)[a]	2.0 (2.0)[b]	0.5 (1.0)[b]	**<0.001**
Maximum depth of charcoal	35.4 (9.86)	24.7 (9.86)	20.8 (8.46)	19.0 (9.56)	30.0 (8.16)	0.055
Minimal depth of charcoal in mineral soil	19.4 (10.92)[ab]	8.6 (6.24)[ac]	4.7 (4.35)[c]	2.0 (2.00)[abc]	–3.8 (1.50)[b]	**<0.001**
Maximum depth of charcoal in mineral soil	35.4 (9.86)[a]	19.9 (9.4)[ab]	14.8 (8.77)[b]	19.0 (9.56)[ab]	25.8 (7.8)[ab]	**0.006**
Thickness of layer consisting of charcoal	16.0 (11.64)	11.6 (10.30)	10.1 (7.70)	17.0 (9.20)	29.5 (9.00)	0.052
Upper border of charcoal-rich layer	28.2 (8.35)[a]	13.8 (6.15)[b]	10.8 (3.08)[b]	2.3 (3.20)[a]	13.5 (7.90)[ab]	**<0.001**
Lower border of charcoal-rich layer	33.4 (8.79)[ab]	21.4 (6.15)[ac]	16.4 (4.98)[cd]	9.5 (3.70)[bd]	19.8 (7.32)[abcd]	**<0.001**
Thickness of charcoal-rich layer	5.2 (4.15)	7.0 (6.50)	5.7 (2.82)	7.0 (0.82)	6.3 (4.79)	0.939
Upper border of charcoal-rich layer in mineral soil	28.2 (8.35)[a]	9.3 (6.29)[b]	4.8 (3.75)[b]	2.3 (3.20)[ab]	9.3 (6.95)[ab]	**<0.001**
Lower border of charcoal-rich layer in mineral soil	33.4 (8.79)[a]	16.9 (6.56)[b]	10.3 (5.02)[c]	9.5 (3.70)[abc]	15.5 (6.61)[abc]	**<0.001**
Litter thickness	0.0 (0.00)[a]	4.7 (2.04)[b]	6.1 (2.43)[b]	0.0 (0.00)[a]	4.3 (0.96)[ab]	**<0.001**
Humus thickness	32.0 (11.55)[a]	15.3 (6.30)[b]	9.9 (5.55)[c]	25.0 (2.94)[a]	0.0 (0.00)[d]	**<0.001**

Note: A – arable fields, B – *buschland*, F – forest, E – experimental slash-and-burn field, W – recent forest fire site. *P*-value shows the overall statistical significance of between groups' differences (the Kruskal-Wallis test), while superscript letters indicate the statistical significance of pairwise differences (means without a common letter are statistically significantly different, $p \leq 0.05$, the pairwise Wilcoxon tests followed by the Holm correction for multiple testing).

(33.4 cm) and forests (16.4 cm). The lower border of the charcoal-rich horizon was in a medium position in *buschlands* (21.4 cm) but was not different from other historical land-use groups. In terms of mineral soil, the differences were obvious for arable fields (upper border 28.2 cm and lower level 33.4 cm). The upper level of the charcoal-rich layer was not significantly different for forests and *buschlands* (9.3 and 4.8 cm, respectively), but the lower border was different (16.9 and 10.3 cm, respectively) (Table 1).

The results of the correlation analysis (Table 2) demonstrated that the depth of charcoal in the soil was correlated with the groups, which reflect the agricultural land-use duration and methods. The correlation with the depth of the charcoal-rich layer was higher than the correlation with the minimal and maximum depths of charcoal fragments. The strongest positive correlation was revealed between land-use duration and cultivation method and the lower border of the charcoal-rich layer in mineral soil.

In former slash-and-burn cultivation sites, the charcoal was dated 1669–1945 calAD in the humus layer and was out of dating range at one site (Table 3). In the illuvial layer, the charcoal was much older at one site, while at another, it was not remarkably different and might be out of calibration range.

At one forest site, the dates (1464–1796 calAD) were a little earlier than those found in *buschlands,* but the other forest site was dated from 3913 calBC to 3639 calBC.

Table 2. Correlation with land-use duration and methods

Characteristic	Correlation
Minimal depth of charcoal	**0.40**
Maximum depth of charcoal	**0.33**
Minimal depth of charcoal in mineral soil	**0.52**
Maximum depth of charcoal in mineral soil	**0.43**
Thickness of charcoal-consisting layer	0.08
Upper border of charcoal-rich layer	**0.57**
Lower border of charcoal-rich layer	**0.62**
Minimal depth of charcoal-rich layer in mineral soil	**0.63**
Maximum depth of charcoal-rich layer in mineral soil	**0.67**
Thickness of charcoal-rich layer	0.03
Litter thickness	**–0.48**
Humus thickness	**0.61**

Note: Statistically significant ($p < 0.05$) correlation coefficients are presented in bold.

Table 3. Results of radiocarbon dating

Sample Identification code	Land-use group	Coordinates in EPSG:3301 projection (BL)	Depth, cm	Date BP	Calibrated AD (probability 95.4%)		Weighted average calAD	Error of weighted average calAD
					from	to		
Poz-70010	B	57.688652	0–18	95 ± 30	1682	1931*	1789	89
Poz-70018		26.422098	18–35	925 ± 30	1026	1182	1101	42
Poz-70009	B	57.718055	7–20	140 ± 30	1669	1945*	1805	82
Poz-70007		26.473986	20–50	185 ± 30	1650	>1917*	1786	90
Tln3577	F	57.706653 26.46886	20–30	297 ± 50	1464	1796	1582	77
Tln3877	F	57.76167 26.465197	33	4940 ± 50	–3913	–3639	–3731	63

Note: Land-use groups: B – *buschland*, F – forest. * Date may extend 1950; probability that date is recent that 1917 is 20.8%.

Discussion and conclusions

Charcoal is widespread in the soils of the study area. The presence of charcoal in soil samples was higher than registered in Norway by Ohlson et al. (2009), where macroscopic charcoal was found in the 50% of soil samples.

As macroscopic charcoal indicates local burnings, it could be concluded that fire was present in all observed types of land use. In two former slash-and-burn fields where charcoal was not found, the charcoal was probably fragmented or eroded due to tillage because these sites were regularly cultivated arable fields at the beginning of the 20th century.

The depth characteristics of soil charcoal revealed a correlation with duration and methods of land use. The most indicative characteristic was the average maximal depth of the charcoal-rich layer. The charcoal location in forests must be observed according to mineral soil because the thickness of the litter layer depends on the land-use history (Tomson et al. 2018).

In the recent forest fire locations, the charcoal was found in the highest position, like in Sweden, where wildfire charcoal has been registered in the surface of mineral soil (Weimarck 1968). The charcoal produced by the last fire, which was a low-intensity ground fire, contained only single burned fragments of corns and branches found in the litter. Most of the fires in boreal forests are ground fires (Lehtonen and Huttunen 1997, Granström 1999). Often, all the litter layer and ground vegetation is not destroyed. This kind of fire does not produce much wood charcoal, and charcoal erosion by water flow after a fire is blocked by the partly maintained vegetation and litter. Charcoal might pass downwards in the litter layer over time due to the decomposition of the litter beneath. Therefore, the depth of charcoal must be examined in relation to the mineral soil. In the recent forest fire sites, most of the charcoal from earlier fires was found relatively lower; therefore, the average depth characteristics were much greater.

In the forest sites of the 19th century, charcoal was not found in the litter; as expected, charcoal was found directly under the litter layer on the surface of mineral soil in only nine places. The main reason for the decomposition of charcoal is oxidation that needs well-aerated conditions (Nguyen and Lehmann 2009). Freezing and thawing promote fragmentation of the charcoal (Carcaillet and Talon 2001, Czimczik and Masiello 2007). All these processes are most effective in the soil surface layer. More charcoal was found in mineral soil. Charcoal accumulation into clusters – typical in the case of intense stand-replacing forest fires (Bobrovsky 2010) – was found in one forest site from a depth of 33 cm and dated back about 6,000 years. Similar charcoal complexes at depths of 40–80 cm have been described in Russia, which have been buried because of tree uprooting by windthrow after a fire (Bobrovsky 2010). Still, most of the charcoal in the forest sites was found higher (up to 16.4 cm on average) and other pedoturbation mechanisms must be considered. Wild boars might have mixed the superficial layers, as 67% of stands analysed during the previous study in the same sites were, to some extent, damaged by these animals; no differences were found between former slash-and-burn sites and forests (Tomson et al. 2018). An uneven distribution of charcoal must be expected in this case. The charcoal left in the ground could be translocated after tree fall in the process of soil falling from uprooted root collars, which would disperse forest fire charcoal into higher positions than accumulation in tree fall depressions. Single pieces in mixed soil material could be found in this case. Repeated uprooting in the same place could translocate the charcoal many times. In numerous sites with podzols was visible a dark grey layer in the upper part of the illuvial horizon. This layer is probably caused by infiltration of microscopic charcoal because of freeze and thaw and roots.

In the cultivated lands, the initial charcoal translocation is caused by ploughing and harrowing. For slash-and-burn fields, the depth of charcoal is expected to correlate with historical tools. In central Russia, Bobrovky et al. (2019) registered charcoal in slash-and-burn cultivation layers at a depth of 4–20 cm. In the present study, the lower border of a charcoal-rich layer was similar (21.4 cm). However, the charcoal was found deeper (24.7 cm on average), even according to mineral soil (19.9 cm on average). Consequently, part of the charcoal cannot be transported into the soil by tillage. It is well-known that earthworms mix the humus layer in soil (Darwin 1881). Also, in field experiments, charcoal has been incorporated into the soil profile mainly by earthworms (Eckmeier et al. 2007, Major et al. 2010). Terhivuo (1989) found that the activity of earthworms is much lower in boreal coniferous forests than in meadows and deciduous forests and is limited to the litter layer. In the case of rotational slash-and-burn cultivation, the land was covered with grasses and deciduous trees most of the time; therefore, the activity of endogeic earthworms must have been more intense than it was in continuous forest land with coniferous forests. During fieldwork in former *buschland*s, it was easier to find charcoal in the lower part of the humus because there were more large fragments and groups of charcoal than there were in the upper part of the topsoil. In cultivated lands, the charcoal location has been affected in addition to the vertical soil mixing, also by horizontal soil movement. The ploughing and harrowing smoothened the originally uneven surface of the forest floor (Ponomarenko et al. 2019) and the later ploughing level did not reach to charcoal that was buried in the initial micro-depression of the natural surface. Therefore, the larger fragments of charcoal were found at the bottom of the humus layer.

In arable fields that were cultivated during the 20th century, it is expected that mechanised ploughing has an effect up to a depth of 20–30 cm. Most of the charcoal was found a little deeper, in the transition from humus to subsoil. This location is like charcoal buried in slash-and-burn fields due to horizontal soil translocation and indicates that charcoal must have been derived from burnings before the permanent arable was established. The fire was used for land clearance to establish permanent arable fields. Also, numerous permanent fields were developed from swiddens (Ligi 1963) that would have left the charcoal to the arable soil. In depressions and foothills, the charcoal is buried due to soil erosion. In the upper layers of arable fields, the charcoal must be fragmented to the microscopic particles not registered in the present study. However, the finds of charcoal in the subsoil at depths of 50 cm, even on hilltops, suggest that the signs of forest fires and subsequent bioturbation from the time before tillage could remain in the soil profile. Likely, charcoal from pre-cultivation forest fires can still be found in the slash-and-burn sites and arable fields. Also, Bobrovsky et al. (2019) stated that charcoal could be found both from agriculture and forest fires within the same soil profile.

Though the peculiarities of recent forest fires and experimental slash-and-burn charcoal were not confirmed by statistical tests due to the small number of sites, in the experimental field, the recent charcoal-rich ploughing layer was well-distinguished. The depth of charcoal rich layer must reflect the soil mixing depth by historical slash-and-burn cultivation, because in the experiment the copies of historical tools were used. The older charcoal in the deeper layers was less numerous. No charcoal was found in the ground, probably due to decomposition and fragmentation.

The single pieces with diameter 1–2 mm and not connected to any pedoturbation traces were found under the humus layer in all land-use types. Therefore, the maximal depth was not different between land-use groups, and the thickness of the layer consisting of charcoal did not reveal a correlation with land-use duration and methods. It can be assumed that these fragments are the result of forest fires from earlier periods, but the mechanism of translocation is unclear. Bobrovsky and Loyko (2016) stated that in Luvisols, charcoal pieces with a diameter of no more than 0.2 mm could be transported with water at a depth of more than 1 m, but in the present study, the size of particles was much bigger. Carcaillet (2001) suggested that anenic earthworms move the charcoal deeper into mineral soil.

Against expectations that tillage would mix the charcoal evenly into the cultivation layer, the thickness of the charcoal-rich layer did not correlate with land-use methods. Therefore, it is likely that some of the observed mesotrophic forest sites were also affected by recurrent slash-and-burn cultivation but were not mapped as forest land in the 19th century. The three sites with ploughing lynchets confirm this assumption. Therefore, the average characteristics of the charcoal location of forests and *buschland*s are not always different.

Charcoal from the upper layers of former rotational slash-and-burn cultivation sites was dated to the period from the 17th century to the 20th century. These dates correlate with the decline of slash-and-burn cultivation described in Estonian literature (Ligi 1963, Jääts et al. 2010). The fact that samples from slash and burn sites had some probabilities of being produced later in the 20th century does not affect the conclusions because, from the previous study is known, that regular slash and burn practices in the region had finished at that time (Jääts et al. 2010). The illuvial layer of slash and burn cultivated soils probablu contain both cultivation charcoal and also wildfire charcoal due to pedoturbation. Radiocarbon dating distinguished forest fire charcoal that was thousands of years old in the lower layers from slash-and-burn cultivation charcoal. The second date from the forest belonged to a slightly earlier period than slash-and-burn charcoal. More datings could ensure the origin of different charcoal patterns.

This study demonstrates that a considerable proportion of forest soil charcoal could originate from historical slash-and-burn cultivation in areas, where the swiddens were common until the 19th century. The charcoal location in the soil is related to agricultural land use duration and methods at different intensities. The charcoal locates deeper in soils of permanent arable fields than in long time forests soils but in the former slash and burn cultivation soils the differences are not significant. The soil charcoal could originate from different fire events; a large variation complicates the interpretation of data. The high variability of characteristics reflects that the same land-use groups have been affected by different pedoturbation processes and that identified land-use groups could be affected by different land-use before mapping in the 19th century. A better understanding of charcoal locations in forest soil allows to identify the past fire regime and provides a better understanding of forest succession and background information to predict the impact of climate changes. Therefore, the future studies of charcoal origin and amount are needed in the Baltic region.

References

Astover, A., Reintam, E., Leedu, E. and Kõlli, R. 2013. Muldade väliuurimine [Field Study of Soils]. Eesti Maaülikool, Tartu, 70 pp. (in Estonian).

BETA. 2021. Radiocarbon Dating and Archaeology. BETA Analytic Testing Laboratory. BETA Analytic Inc., Miami, FLA, USA. Available online at: https://www.radiocarbon.com/archaeology.htm.

Bobrovsky, M.V. 2010. Lesnye pochvy Evropeiskoi Rossii: bioticheskie i antropogennye faktory formirovaniia [Forest soil in European Russia: biotic and anthropogenic factors in pedogenesis]. KMK Scientific Press, Moscow, 359 pp. (in Russian with English summary).

Bobrovsky, M.V. and Loyko, S.V. 2016. Patterns of pedoturbation by tree uprooting in forest soils. *Russian Journal of Ecosystem Ecology* 1: 1–22. https://doi.org/10.21685/2500-0578-2016-1-3.

Bobrovsky, M.V., Kupriaynov, D.A. and Khanina, L.G. 2019. Anthracological and morphological analysis of soils for the reconstruction of the forest ecosystem history (Meshchera Lowlands, Russia). *Quaternary International* 516: 70–82. https://doi.org/10.1016/j.quaint.2018.06.033.

Bronk Ramsey, C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(1): 337–360.

Carcaillet, C. 1998. A spatially precise study of fires, climate and human impact within the Maurienne valley, North French Alps. *Journal of Ecology* 86: 384-396. https://doi.org/10.1046/j.1365-2745.1998.00267.x.

Carcaillet, C. 2001. Are Holocene wood-charcoal fragments stratified in alpine and subalpine soils? Evidence from the Alps based on AMS 14C dates. *The Holocene* 11(2): 231– 242. https://doi.org/10.1191/095968301674071040.

Carcaillet, C. and Talon, B. 2001. Soil Carbon Sequestration by Holocene Fires Inferred from Soil Charcoal in the Dry French Alps. *Arctic, Antarctic, and Alpine Research* 33(3): 282–288. https://doi.org/10.2307/1552235.

Czimczik, C.I. and Masiello, C.A. 2007. Controls on black carbon storage in soils. *Global Biogeochemical Cycles* 21: GB3005. https://doi.org/10.1029/2006GB002798.

Czimczik, C.I., Schmidt, M.W.I. and Schulze, E.-D. 2005. Effects of increasing fire frequency on black carbon and organic matter in Podzols of Siberian Scots pine forests. *European Journal of Soil Science* 56: 417–428. https://doi.org/10.1111/j.1365-2389.2004.00665.x.

Darwin, C.R. 1881. The formation of vegetable mould, through the action of worms, with observations on their habits. London: John Murray. 5th thousand. Available online at: http://darwin-online.org.uk/EditorialIntroductions/Freeman_VegetableMouldandWorms.html. [Cited 19 Jan 2018].

Eckmeier, E., Gerlach, R., Skjemstad, J.O., Ehrmann, O. and Schmidt, M.W.I. 2007. Minor changes in soil organic carbon and charcoal concentrations detected in a temperate deciduous forest a year after an experimental slash-and-burn. *Biogeosciences* 4: 377–383. https://doi.org/10.5194/bg-4-377-2007.

Estonian Land Board. 2019. Estonian Land Board Web Map Server Historical Map Application. *URL*: xgis.maaamet.ee [Cited in 20 Dec 2019].

Gabet, E.J., Reichman, O.J. and Seabloom, E.W. 2003. The effects of bioturbation on soil processes and sediment transport. *The Annual Review of Earth and Planetary Science* 31: 249–273. https://doi.org/10.1146/annurev.earth.31.100901.141314.

Gavin, D.G. 2003. Forest soil disturbance intervals inferred from soil charcoal radiocarbon dates. *Canadian Journal of Forest Research* 33: 2514–2518. https://doi.org/10.1139/x03-185.

Granström, A. 1996. Fire ecology in Sweden and future use of fire for maintaining biodiversity. In: Goldammer, J.G. and Furyaev, V.V. (Eds.) Fire in Ecosystems of Boreal Eurasia. Kluwer Academic Publishers, Dordrecht, p. 445–452, ISBN 0-7923-4137-6.

Hamilton, H. 1997. Slash and burn in the history of Swedish forests. *Rural Development Forestry Network Paper* 21f: 19–24. Available online at: http://www.odi.org.uk/publications/754-slashburn-history-swedish-forest [Cited in 20 Dec 2019].

Jääts, L., Kihno, K., Tomson, P. and Konsa, M. 2010. Tracing fire cultivation in Estonia. *Forestry Studies* 53: 53–65. https://doi.org/10.2478/v10132-011-0089-3.

Jääts, L., Konsa, M., Kihno, K. and Tomson, P. 2011. Fire Cultivation in Estonian Cultural Landscapes. The Space of Culture – the Place of Nature in Estonia and Beyond. (Approaches to Culture Theory; 1), Tartu Ülikooli Kirjastus, Tartu, p. 165–180.

Kasin, I., Ellingsen, V.M., Asplund, J. and Ohlson, M. 2017. Spatial and temporal dynamics of the soil charcoal pool in relation to fire history in a boreal forest landscape. *Canadian Journal of Forest Research* 47(1): 28–35. https://doi.org/10.1139/cjfr-2016-0233.

Keskkonnaamet. 2007. Karula rahvuspargi kaitsekorralduskava 2008–2018 [Management Plan of Karula National Park 2008–2019]. Available online at: https://www.kaitsealad.ee/sites/default/files/Karula%20rahvuspark/Kaitsekorralduse%20dokumendid/Karula_RP_KKK_2008-2018.pdf [Cited in 20 Dec 2019] (in Estonian).

Kukuļs, I., Kļaviņš, M., Nikodemus, O., Kasparinskis, R. and Brūmelis, G. 2019. Changes in soil organic matter and soil humic substances following the afforestation of former agricultural lands in the boreal-nemoralecotone (Latvia). *Geoderma Regional* 16: 1–11, e00213. https://doi.org/10.1016/j.geodrs.2019.e00213.

Kuum, E. 1971. Teraviljade saakide dünaamikast Eestis [On the dynamics of grain yields in Estonia]. In: Viileberg, K. (Ed.) Eesti Põllumajanduse Akadeemia teaduslike tööde kogumik 72. Põllukultuuride saagikuse suurenemise teoreetilised alused [Collection of researches of the Estonian Academy of Agriculture 72. Theoretical bases of increasing the yields of crops]. Eesti Põllumajanduse Akadeemia, Tartu, p. 81–97 (in Estonian).

Kõlli, R. 2012. Eesti mullad [Estonian soils]. In: Astover, A., Kõlli, R., Roostalu, H., Reintam, E. and Leedu, E. (Eds.) Mullateadus [Soil Science]. Eesti Maaülikool, Tartu, p. 306–398 (in Estonian).

Lehtonen, H. and Huttunen, P. 1997. History of forest fires in eastern Finland from the 15th century AD – the possible effects of slash-and-burn cultivation. *The Holocene* 7: 223– 228. https://doi.org/10.1177%2F095968369700700210.

Ligi, H. 1963. Põllumajanduslik maakasutus Eestis XVI–XVII sajandil [Agricultural land use in Estonia in the XVI–XVII centuries]. Eesti NSV Teaduste Akadeemia Ajaloo Instituut, Tallinn, 137 pp. (in Estonian).

Ludemann, T. 2003. Large-scale reconstruction of ancient forest vegetation by anthracology – a contribution from the Black Forest. *Phytocoenologia* 33(4): 645–666. https://doi.org/10.1127/0340-269X/2003/0033-0645.

Lynch, J.A., Clark, J.C. and Stocks, B.J. 2004. Charcoal production, dispersal, and deposition from the Fort Providence experimental fire: interpreting fire regimes from charcoal records in boreal forests. *Canadian Journal of Forest Research* 34: 1642–1656. https://doi.org/10.1139/X04-071.

Major, J., Lehmann, J., Rondon, M. and Goodale, C. 2010. Fate of soil-applied black carbon: downward migration, leaching and soil respiration. *Global Change Biology* 16: 1366–1379. https://doi.org/10.1111/j.1365-2486.2009.02044.

Nguyen, B.T. and Lehmann, J. 2009. Black carbon decomposition under varying water regimes. *Organic Geochemistry* 40: 846–853. https://doi.org/10.1016/j.orggeochem.2009.05.004.

Ohlson, M. and Tryterud, E. 2000. Interpretation of the charcoal record in forest soils: forest fires and their production and deposition of macroscopic charcoal. *The Holocene* 10(4): 519–525. https://doi.org/10.1191/095968300667442551.

Ohlson, M., Dahlberg, B., Økland, T., Brown, K.J. and Halvorsen, R. 2009. The charcoal carbon pool in boreal forest soils. *Nature Geoscience* 2(10): 692–695. https://doi.org/10.1038/ngeo617.

OxCal. 2017. OxCal program, version 4.3. Research Lab for Archaeology and the History of Art, 1 South Parks Road, Oxford OX1 3TG, UK. URL: https://c14.arch.ox.ac.uk/oxcalhelp/hlp_contents.html.

Paal, J. 1997. Eesti taimkatte kasvukohatüüpide klassifikatsioon [Classification of Estonian vegetation site types]. Keskkonnaministeeriumi Info- ja Tehnokeskus, Tallinn, 297 pp. (in Estonian).

Pärdi, H. 1998. Talumajandus [Farm management]. In: Viires, A. and Vunder, E. (Eds.) Eesti rahvakultuur [Estonian National

Culture]. Eesti Entsüklopeediakirjastus, Tallinn, p. 73–120 (in Estonian).

Poska, A., Väli, V., Kama, P., Tomson, P., Vassiljev, J. and Kihno, K. 2017. Karula kõrgustiku taimkatte ning inimasustuse pärastjääaegne areng [Development of vegetation and settlements after the Ice Age in the Karula Upland]. In: Järvet, A. (Ed.) Eesti Geograafia Seltsi aastaraamat. Vali Press OÜ, Tallinn, p. 25–43 (in Estonian with English summary).

Ponomarenko, E. and Anderson, D.W. 2013. Signature of forest fires in prairie soils. In: Damblon, F. (Ed.) Charcoal and microcharcoal. Continental records. Acts of the 4th International Meeting of Anthracology. Proceedings of the 4th International Meeting of Anthracology. BAR International Series 2486. Archaeopress, Oxford, p. 195–202.

Ponomarenko, E., Ershova, E., Tomson, P. and Bakumenko, V.A. 2019. Multi-proxy analysis of sandy soils in historical slash-and-burn sites: Karula case study. *Quaternary International* 516: 190–206. https://doi.org/10.1016/j.quaint.2018.10.016.

R Core Team. 2020. R: A language and environment for statistical computing. Version 3.3.3. R Foundation for Statistical Computing, Vienna, Austria. URL: www.R-project.org.

Robin, V. and Nelle, O. 2014. Contribution to the reconstruction of central European fire history, based on the soil charcoal analysis of study sites in northern and central Germany. *Vegetation History and Archaeobotany* 23(Suppl 1): S51– S65. https://doi.org/10.1007/s00334-014-0438-2.

Robin, V., Bork, H.-R., Nadeau, M.-J. and Nelle, O. 2014. Fire and forest history of central European low mountain forest sites based on soil charcoal analysis: The case of the eastern Harz. *The Holocene* 2(1): 35–47. https://doi.org/10.1177/0959683613515727.

Scott, A.C. 2010. Charcoal recognition, taphonomy and uses in palaeo-environmental analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 291: 11–39. https://doi.org/10.1016/j.palaeo.2009.12.012.

Sigaut, F. 1979. Swidden cultivation in Europe. A question for tropical anthropologists. *Social Science Information* 18(4- 5): 679–694.

Talon, B., Payette, S., Filion, L. and Delwaide, A. 2005. Reconstruction of the long-term fire history of an old-growth deciduous forest in Southern Québec, Canada, from charred wood in mineral soils. *Quaternary Research* 64(1): 36–43. https://doi.org/10.1016/j.yqres.2005.03.003.

Tarand, A., Jaagus, J. and Kallis, A. 2013. Eesti kliima minevikus ja tänapäeval [Estonian climate in past and present]. University of Tartu Press, Tartu, 632 pp. (in Estonian).

Terhivuo, J. 1989. The Lumbricidae (Oligochaeta) of southern Finland: species assemblages, numbers, biomass and respiration. *Annales Zoologici Fennici* 26: 1–23. Available online at: http://www.sekj.org/PDF/anzf26/anz26-001-023.pdf [Cited 19 January 2018].

Tomson, P., Kaart, T. and Sepp, K. 2018. Role of 19th-century rotational slash-and-burn cultivation in the development of boreal forests in southern Estonia and implications for forest management. *Forest Ecology and Management* 409(1): 845–862. https://doi.org/10.1016/j.foreco.2017.12.005.

Wallenius, T. 2002. Forest age distribution and traces of past fires in a natural boreal landscape dominated by *Picea abies*. *Silva Fennica* 36(1): 201–211. https://doi.org/10.14214/sf.558.

Weimarck, G. 1968. Ulfshult: investigations concerning the use of soil and forest in Ulfshult, parish of Örkened, during the last 250 years. Ulfshult at the 1717 and 1747 surveys by Gunhild Weimarck. C.W.K. Gleerup, Lund, 66 pp.

Appendix

Appendix 1. Table of maps

	Mapped area	Title of map	Drawn	Scale	Reference code of Estonian National Archive
1	Vana-Antsla manor	Charte von dem privaten Gute Alt-Anzen	1871-72	1:20800	EAA.3724.4.1838
2	Boose manor	Charte von dem privaten Gute Bosenhof	1871-72	1:18081	EAA.3724.4.1867
3	Karula manor	Situations Charte von dem Gute Carolen	1867	1:20800	EAA.3724.5.2803