Quaternary International 516 (2019) 190–206

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

A multi-proxy analysis of sandy soils in historical slash-and-burn sites: A case study from southern Estonia

Elena Ponomarenko[a,*], Pille Tomson[b], Ekaterina Ershova[c], Varvara Bakumenko[c]

[a] University of Ottawa, Ottawa, Canada
[b] Estonian University of Life Sciences, Tartu, Estonia
[c] Moscow State University, Moscow, Russia

ABSTRACT

An experimental slash-and-burn (SABC) site and a site included in the cycle of SABC in 19th century were used as a reference to describe a signature of this cultivation method in sandy soils. Documented slash-and-burn layers were compared to pyrogenic layers from other sites and time periods in attempt to differentiate between results of slash-and-burn cultivation and wild fires.

The swidden layers in sandy soils appeared as 5 to 10- cm thick, dark-coloured "humus" layers with a characteristic scalloped lower boundary, formed by numerous constructions of fossorial insects, predominantly sweat bees. The dark coloration originates from high concentrations of charcoal fragments with a median length of 4 to 5 mm, pebbly shape and silt coating, uniformly distributed within the swidden layers. A low proportion of bark and presence of foliage (buds and needles) in charcoal assemblages are characteristic for SABC layers. The phytolith content of SABC layers varied from tens to hundreds of thousands per gram of soil, with up to 50% of phytoliths being charred. The SABC layers contained dendritic and/or panicoid phytoliths and cereal glumes and paleas indicative of *in situ* cultivation of crops. The palynological signature of swiddens is a pollen spectrum of forest ecosystem with a proportion of fire-dependant taxa, such as *Onagraceae* pollen and *Marshantia* spores.

1. Introduction

Slash-and-burn cultivation is one of many types of so called shifting cultivation, - the land-use system that alternates cropping and fallows. Burning forest for farming is the first stage of land clearance in many agricultural systems, but the slash-and-burn (or swidden) agriculture is the farming technique in which burned and cleared sites are cropped for shorter periods than the follow-up fallow (Conklin, 1961).

It's believed that the slash-and-burn cultivation (SABC) was practiced in northern Europe at least since the Bronze Age (4 to 5ka ago), with the extent of the areas affected by SABC increasing drastically in the Iron Age, when the iron implements became available. Until the 1900-s, SABC was still practiced in the boreal forests of Estonia and Sweden, and until the 1930-s in Finland and Russia. The SABC subsistence of archaeological cultures is inferred from the evidence for plant cultivation in the absence of agricultural implements and characteristic frequent changes in the location of dwelling sites (Lavento, 2012). Due to the elusiveness of the archaeological evidence, the visibility of the slash-and-burn agriculture is inferred mainly from palynological and carpological analyses (e.g., Tolonen, 1978; Bradshaw et al., 1997; Alenius et al., 2008). Most palynological data comes from the lakes and bogs and does not allow for a site-oriented reconstruction. There is no specific pollen spectrum attributed to the swidden cultivation, but a combination of frequent and recurrent successions in tree pollen with the presence of charcoal in lake sediments has been accepted as palynological evidence for SABC (Vuorela 1986; Lageras, 1996).

Historical descriptions outline the following technological components of the SABC (Petrov, 1968): the conversion, cropping, and fallow.

At the conversion stage, trees were either girdled (in old forests), or cut (in young forests); left for drying and then burned, the wood ash serving as a fertilizer. The burning took place in the spring for spring-sown crops and in the fall for autumn-sown crops.

The cropping stage lasted from 1 to 5 years depending on the soil quality. After some years the field have lost its fertility and the swidden was abandoned to forest fallow. The duration of the forest fallow, and of the entire SABC cycle changed through time, becoming shorter as the population density was increasing (Petrov, 1968).

In Estonia, the regular burning of old forests ceased already in the seventeenth century due to the lack of timber (Etverk, 1974). In young forests the regular burning cycle took place every 30 years in the seventeenth century with the interval between burnings decreasing to 15 to 20 years in the nineteenth century (Meikar and Uri, 2000).

In the 17th to 19th century, the areas recurrently used for swidden

---

[*] Corresponding author.

E-mail addresses: ecosystemarchaeology@gmail.com (E. Ponomarenko), Pille.Tomson@emu.ee (P. Tomson), ekaterinagershova@mail.ru (E. Ershova), barbara-98@mail.ru (V. Bakumenko).

https://doi.org/10.1016/j.quaint.2018.10.016
Received 2 February 2018; Received in revised form 15 October 2018; Accepted 15 October 2018

cultivation in Estonia were termed *buschlands* in the local Baltic German dialect (Ligi, 1963). The term *buschland* refers only to the land use, not the tree cover life form. The *buschlands* were covered by young trees, predominantly silver birch (*Betula pendula*), gray alder (*Alnus incana*) and Norway spruce (*Picea abies*) (Ligi, 1963), located either (mainly) on hills, or in flat areas remote from homesteads. (Tomson et al., 2015).

Every year, the trees were cut and burned in a 0.5 to 1 ha patch of the *buschland*. After burning the seeds were put into the soil using a harrow or ard. Rye, barley and turnip were the most common crops in slash-and-burn fields. A site was used for crop cultivation for 2 to 5 years, depending on the soil fertility; once the soil was depleted, the land was left fallow for 15 to 20 years (Ligi, 1963). In 19th century, cycles of slash-and-burn management were regulated by the agrarian law (Lihwlandi-ma tallorahva Seädus, 1820) implying at least 20 years of the fallow stage. The *buschlands* were used for grazing in the first 2–3 years of the forest fallow. Once trees had begun to colonize the abandoned swidden, they were partially cut and collected for firewood.

The *buschlands* were often located on hills, as ploughing and manuring of such positions were impractical, coexisting with the permanent cultivation of the toe slopes and flat lowlands between the hills. The outskirts of the *buschlands* adjacent to permanent fields could be included in the fields and tilled from time to time. In the eighteenth century approximately half of the annual crop yield was harvested from slash-and-burn fields (Ligi, 1963). In Karula region the *buschlands* comprised up to 35% of all agricultural lands in the 19th century, while meadows and permanent fields occupied 28 and 25% respectively. By the beginning of the 20th century, the *buschlands* had declined, with 72% being converted into arable land, 19% into forest and 9% into meadows. By the end of the 20th century, about 80% of the former *buschlands* were turned into forest (Tomson et al., 2018, Tomson et al., 2015).

Today the main species in the forests formed on the *buschlands* in Karula are pine (41%), birch (31%), gray alder (13%), spruce (13%) and aspen (2%). The soil types on *buschlands* are mainly Albeluvisols (Tomson et al., 2016).

As the signature of slash-and-burn cultivation method in the soil is yet unknown, the presence of well-documented experimental and historical swiddens in Karula presents an opportunity to describe diagnostic features indicative of soils affected by this cultivation.

The main goal of this case study was to find some specific, preferably morphological and semi-quantitative soil features associated with the past SABC. Diagnostic soil features observed in documented SABC sites were further applied to analyse the origins of pyrogenic layers from other sites and time periods. This paper describes the first results of the palynological, anthracological, phytolith, and trace fossil analyses of sandy forest soils affected by the slash-and-burn cultivation in the 16th to 19th centuries AD.

The working hypothesis/assumptions

The SABC technology allows us to expect certain morphological and analytical characteristics of soils affected by this type of cultivation.

1) Traces of the SABC in the soil expected to be considerably shallow, and the probability of their preservation would be higher in the settings with a high deposition rate, such as toe slopes in hummocky terrains;
2) Burning must leave a substantial amount of charcoal in the soil, whereas farming techniques such as raking and harrowing at the conversion stage may distribute the charcoal within the cultivated layer more or less uniformly;
3) Mixing the powdered and comminuted charcoal with the mineral mass would result in the formation of a uniformly-coloured greyish pyrogenic horizon with the depth approximately equal to the stirring/cultivation depth (~7 cm);
4) Charcoal assemblages resulting from burning entire trees on the ground at the SABC conversion stage must contain a proportion of charred needles, leafs or buds. The proportion of charcoalified bark will be low due to its fast and deep combustion. In contrast, the majority of charcoal resulting from forest wildfires is expected to be charcoalified bark, as ground fires affect mainly this part of (living) trees. The rest of the tree may die-off after fires leaving behind dead wood, not charcoal. Furthermore, wildfires attract a suite of saprotrophic insects, and finding their numerous remains in association with charcoalified bark may be indicative of past wildfires. Plant ash consists of carbonates and phytoliths (plant opal), that comprise several percent of the burned tree foliage and grass biomass. In contrast to natural fires that rarely burn a large proportion of biomass into ash, the SABC aims at deep ashing of all wooden debris, including the phytolith-rich foliage. The deep ashing at the conversion stage of the SABC may lead to the accumulation of a substantial amount of phytoliths in swidden layers;
5) We can expect the presence of phytoliths of crop plants within the tilled layer;
6) Initially (at the early stages of the agricultural colonization of the landscape) the swiddens at their cropping stage were small openings in the forest. The surrounding area remained forested, and abandoned swiddens could be reforested rapidly during the fallow stage. Therefore, a pollen signature of the early SABC in the soil must be similar to that of a wildfire.
7) From 17th to 19th centuries, SABC in Estonia involved rotational burning of young deciduous forests that were used for 3 to 5 years as pastures at the fallow stage. Therefore, the pollen of cereals, deciduous trees, and different meadow plants may be associated with this recent type of the SABC. We assumed that the seeds of zoochoric plants, such as *Chenopodiaceae* could be accumulated in the (abandoned) swiddens during grazing episodes at the fallow stage.

2. Setting

Karula National Park is located in south-eastern Estonia (Fig. 1). The climate is moderately continental, with the average temperature −5.9 °C, precipitation 708 mm per year, and the length of the vegetation season 191 days (Estonian Weather Service). The area was located at the ice-marginal zone in the period of deglaciation that formed a strongly-hummocky relief of the area (Karukäpp, 1974). The relief features rolling hills with slopes ranging to 20°, with valleys and depressions between the hills (Fig. 2). Soil parent material are Quaternary sediment moraines that cover Devonian bedrock. The surficial materials are sand and sandy loams. The soil cover includes Histosols, Podzols, Luvisols, and Albeluvisols (Estonian Soil Map).

The modern vegetation of Karula forest is dominated by pine (*Pinus sylvestris*, dominant in 62% forest stands), birch (*Betula pendula*, 25%) spruce (*Picea abies* 10%), and alder (*Alnus incana*, 2%) (State Forest Management Database). According to pollen data, the area was dominated by deciduous forests until approximately 5 thousand years ago; later the dynamics of the forest cover were alternating stages of either birch, or spruce and pine dominance. From approximately 800 years ago spruce declined drastically and pine became a main component of the forests. These dynamics are attributed to the agricultural utilization of the area (Poska et al., 2017). Farming was introduced in south-eastern Estonia in the Bronze Age (1800-500 BC), and became widespread in the Early Iron Age (6th century BC to 1st century AD). The agriculture expanded rapidly at the beginning of Medieval Times in 12th −13th century (Poska et al., 2017).

The region was densely populated for the last two millennia, with all suitable land being used in the agriculture. However, the steep hills could not be maintained as permanent fields; the analysis of archival materials showed that until the end of 19th century steep-sloped hills were used predominantly for SABC, the depressions and valleys between them as hay meadows and pastures, and flat areas and smaller slopes as permanent fields (Fig. 3) (Tomson et al., 2015). The ages of

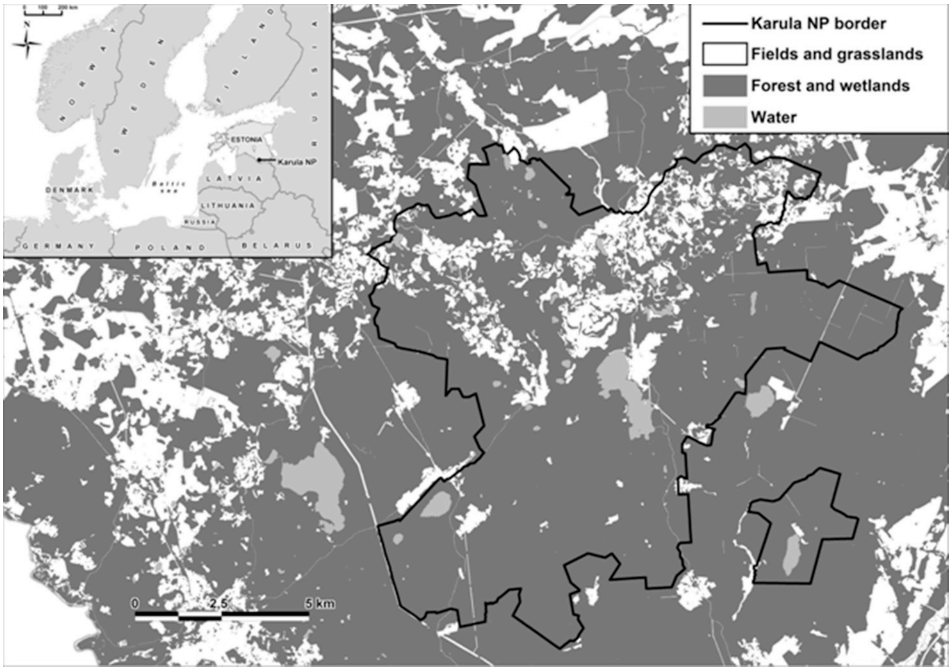

Fig. 1. Study area.

canopy trees in the SABC sites indicate that these trees are either first or second generation of trees recruited after cessation of cultivation, therefore the soil layers affected by the SABC can be still well-preserved in these sites.

In 2007 and 2009 the Karula region hosted an experimental SABC (Jääts et al., 2010).

We examined the following objects (Fig. 3):

An experimental slash-and-burn cultivation site (***ESAB***), 57.734775/26.491743. The site is a former plough land (permanent field) that has been turned into a meadow and is currently used for pasture. The site is located on a steep slope tapering at the base into the flat lowland that acts as a local sediment trap. In August 2007, experimental burning was performed by the Estonian National Museum aiming to replicate the traditional swidden cultivation following the ethnographic descriptions of the 19th century (Jääts et al., 2011). The wood was cut, spread evenly across the field, burned, the soil was ploughed, and then rye seeds were thrown in the ashes and harrowed in. The cultivation was repeated again next year. After the experiment the swidden was regrown by grass and used for pasture since.

The burning took place in an abandoned field with a sparse tree cover, therefore an additional wood had been collected from a nearby area and brought to the site. The volume of firewood was 478 + - 136 m3/ha, and the weight of wood 25.6 + −8 kg/m2 (pers. comm. Marek and Siim Sammul 2007). The distribution of wood biomass by species is presented in Table 1: the majority of trees were birch and alder, with a proportion of pine, spruce, and willow. We examined the experimental swidden layer in 7 test pits within a catena from the upper to the lower boundary of the burned site. Only the surficial layer affected by the experimental SABC was sampled and used for further analyses.

(1) A depression at the toeslope below the experimental burning site in the arable field of the 19th century (***Farmland***), 57.735105/26.492361. The assumption was that the materials eroded from the upper slope positions were rapidly redeposited and accumulated here, preserving the evidence of the previous swidden cultivation cycles that could take place prior to the 19th century. The site is located away from the experimental burning by several tens of meters, and its surficial layers have not been affected by the recent burning. We presented results of our analyses from these neighboring sites on the same diagrams, in order to enable a comparison of the former plough layer in the *Farmland* site with the experimental swidden layer of *ESAB.*

(2) A documented swidden site **(*Buschland*)**, 57.713205/26.485657, localized as a *buschland* on 19th century maps. The site is currently regrown by a forest, with *Pinus sylvestris* forming a canopy, *Picea abies* in the second layer; *Quercus robur*, *Sorbus aucuparia*, and *Frangula alnus* in the understorey, and *Vaccinium myrtillus, Rubus saxatilis*, and green mosses in the ground cover. The average age of the oldest trees is 125 yrs (State Forest Managament database), therefore this appears to be the first generation of trees growing on the abandoned swidden. The soil surface in the site is heavily disturbed by the wild boar who mix upper layers for depth up to 12 cm. We have examined soils in three test pits located in the following settings: 1) a shallow inter-hill depression, 2) a small depression in the upper part of the slope; and 3) position under the root collar of uprooted pine, in the upper part of the slope. It has been suggested that the position under the root collar (between support roots) is protected from the bioturbation during the life tyime of the tree and preserves the soil features that existed in the early stages of tree growth (Ponomarenko, 1990).

(3) A forest site located in the flat lowland bordering a *buschland* slope (***Forest***), 57.716124/26.485672. According to the historic map (Fig. 2), the site was not used in the swidden cycle by the end of the 19th century. The vegetation cover is similar to that of site 2, with pine in the canopy, spruce in the second layer, oak and mountain ash in the understorey and mosses in the ground cover. *Calluna* is a part of the ground cover on the adjacent slope. We examined a test pit located 20 m from the *buschland* toe slope.

3. Methods

The following methods were applied in our case study:

3.1. Soil morphology

Soil profiles were described in seven test pits, 70 to 170 cm deep. We described the soils, depositional layers, and paleosols using standard parameters of soil horizons (thickness, colour using the Munsell

Fig. 2. Relief and locations of study sites.

scale, texture, and horizon boundaries), with a special attention to the presence of trace fossils, such as traces of fossorial animals and tree roots (Ponomarenko, 1999).

Twenty samples of soil mass, ranging in weight from 0.3 to 3.0 kg of were collected from stratigraphic layers for further laboratory analyses. The analysis of large (several kg) samples is required for the representative pedoanthracological analysis (Dutoit et al., 2009). It was impractical to do the full-scale sampling in our case study; therefore, we collected large samples (3 kg) from surficial and buried humus layers, and smaller samples (0.3–0.5 kg) from the other layers, leaving a more thorough quantitative study of the charcoal assemblages for the future.

3.2. Standard pedological analyses

Particle size analysis was carried out using the sieve and pipette method (Kachinskii, 1965), the total carbon content was determined by the chromic acid oxidation (Walkley and Black, 1934), and the content of labile phosphorus was determined by the Kirsanov method: extraction with the 0.2N solution of HCl $5H_2O$ and photocolorimetric determination of a blue phosphorus-molybdenum complex (GOST 54650-2011).

3.3. Pollen analysis

About 10 g of soil mass was subsampled for the pollen analysis. The samples were processed by the technique recommended for mineral soils, using acidification with 10% HCL, boiling in 10% KOH, and centrifuging with heavy liquids (sodium polytungstate) (De Vernal et al., 2010). Counting was done using a light microscope with a magnification from 400 to 1000x with the identification of 250–300 grains per sample. The percentage of pollen taxa was calculated as a percentage of total pollen, and the percentage of spores as a percentage of the total number of pollen and spores.

The pollen extracted from the mineral soil often appears degraded and its identification is more difficult than the identification of pollen from lake and peat deposits. Some taxa simply cannot be identified with a high precision, e.g., identifying pollen of *Cerealia* to the genus level is not possible. In contrast to the pollen spectra of lake sediments, soil pollen is of a local origin, but the proportions of local and regional components in the soil pollen spectra depend on the presence (or

Fig. 3. Fragment of map of Karula manor (Situations Charte von dem Gute Carolen 1867, 1:20,800 EAA.3724.5.2803) with study sites. Pink areas are *buschlands*, gray are permanent arable fields, forests are dark yellow with tree pictograms.

Table 1
Experimental swidden (*ESAB*). The composition of wood and charcoal assemblages.

Species burned	Birch	Alder	Pine	Spruce	Willow
Average diameter, cm	2.5	1.4	5.6	2.1	2.2
Biomass, kg/m3	12	7	2.8	1.9	0.8
Biomass, % of species	46	27.5	11.4	7.7	3.3
Charcoal fragments, %	64	25	7.5		3.5
Charcoal and macrofossils, %	32	12.5	50	3.5	1.8
Charring coefficient	1.4	0.9	0.7/4.4[a]	0/0.5[a]	1.1

[a] Charring coefficient calculated including macrofossils.

dominance) of strong pollen producers in the local vegetation cover. Beside the 'pollen rain', soil pollen can originate from other sources, such as dung, manure, and construction materials brought to the site (Dimbleby, 1985). High concentrations of pollen in these materials may alter the composition of soil pollen spectra.

3.4. Phytolith analysis

The phytoliths are not subjected to the long-distance transport by water and wind to the same degree as pollen; they are always of more or less local origin, and their concentrations in the soil depend on the local vegetation. Phytolith are released from plants during combustion, contributing to the insoluble fraction of ash. All parts of grasses and sedges contain phytoliths, while in trees the majority of phytoliths are produced in reproductive organs and foliage - leafs, needles, and buds. Unlike the phytoliths released through the natural decomposition of plant materials, the phytoliths released by fire can be charred and soot-covered (Piperno, 2006).

About 3 g of soil mass were subsampled for the phytolith analysis. The samples were processed by the technique recommended for mineral soils, using subsequent treatments with concentrated HCl and HNO_3, followed by rinsing and centrifuging; the precipitate was centrifuged at first with 5% solution of sodium hexametaphosphate and then with heavy liquid (KI + CdI2) (Blinnikov, 2013). A total number of extracted phytoliths and a percentage of charred phytoliths were determined upon adding an exotic marker *Lycopodium* tablets, Batch 3862 (Salgado-Labouriau and Rull, 1986). Further, the samples were examined for the presence of the phytolith types diagnostic of *Poaceae* (wild grasses), *Cerealia* (cultivated grasses), and panicoid phytoliths associated with millet and millet-like weeds, and their percentage was calculated where applicable.

3.5. Composition of biogenic components of large fractions

The remaining soil mass was wet-sieved through a 1 mm-mesh sieve and components of the large fractions were analyzed. It has been suggested that the proportions between various components of large fractions may be indicative of the ecosystem and land use types (Ponomarenko, 2017, Ponomarenko et al., 2015). The following components of the > 1 mm fraction were described, both charred and non-charred: *Chenopodiaceae* seeds, body fossils and coprolites of insects, charcoalified bark, and charcoalified foliage: leaves, needles, and buds.

The macrofossils were hand-picked from the large fractions of soil, their numbers per gram of soil and of > 1 mm fraction counted, and percentages of each component calculated. The estimation of numbers of charred fragments is always semi-quantitative due to the fragility of charcoal, but in case of drastic differences in the proportions of various components they can be taken into account.

3.6. Pedoanthracological analysis

Soil charcoal assemblages were described in several ways:

- Morphometry of charred particles including their length, width, and roundness index (length to width ratio). The number of measured fragments varied from 50 to 250, depending on the abundance of charcoal in the samples.
- Taphonomic features: signs of iron deposition and silt-coating on the surface of charcoal fragments (Ponomarenko and Anderson, 2013).
- Charcoal identification was carried out under an incident-light microscope, using wood anatomy manuals (Barefoot and Hankins, 1982; Benkova and Schweingruber, 2004), and reference collections. We intended to identify up to 50 fragments from each layer, but the actual number of identified fragments varied depending on the size and preservation of the charcoal.
- Percentages of each taxon were calculated. It must be noted that such calculations are semi-quantitative, as charcoal is fragile and many fragments of the same tree species may originate from one larger piece of charcoal. Moreover, each assemblage inevitably contains some older charcoal due to erosion and bioturbation (Carcaillet, 2001). Finally, the charcoal of different species is distributed very unevenly in the forest while the best representation of the tree fuel in a soil layer is achieved when the burned material is averaged out within the layer by cultivation (Ponomarenko et al., 2013).

3.7. Radiocarbon dating

Six charcoal samples were submitted for AMS-radiocarbon dating to A.E. Lalonde Laboratory, University of Ottawa. Charcoal in the soil is subjected to redeposition by slope processes and bioturbation, therefore we avoided using composed samples, submitting only single charcoal fragments for radiocarbon dating. In this case each date is valid as a fire date, whereas the age of composed samples rather has a statistical meaning, reflecting the proportions of charcoal of various ages in the sample.

Since charcoal is subjected to redeposition, presence of the charcoal that has been relocated from older layers is always a possibility. To avoid radiocarbon dating of the “invasive” charcoal and resulting age inversions, we aimed to select charcoal fragments with the parameters most common for each layer/assemblage:

- Charcoal fragments of medium/median size were selected, avoiding the largest particles that could be redeposited from other layers
- Charcoal of the taxa that dominated a charcoal assemblage of the layer was selected or, if there was a clear change in the species composition of subsequent layers, the taxa that was indicative of/unique for each layer. The latter did not apply to single fragments of new taxa;
- Charcoal fragments with the surface coating that is typical/observed on most fragments from the layer were selected, e.g. iron-coated/silt-coated/not coated fragments if the majority of fragments were iron-coated, silt-coated, or not coated respectively.

Calibration of the results was done after Bronk Ramsey (2009) (OxCal v.4.1.7).

4. Results and discussion

4.1. Soil stratigraphy

The soil profiles in all four sites exhibited a complex stratigraphy with several dark-coloured (organo-mineral) horizons divided by deposits of a lighter colour (Fig. 4). The buried organo-mineral layers had a distinct steel-gray hue and contained charcoal fragments visible on the section walls; the superposed layers also contained charcoal, but in much lesser quantities. The following types of the dark-coloured layers were observed:

1. Surficial organic layers with a mor humus, typical for coniferous forests (**O**) (Fig. 4 a, b, f);
2. Surficial organo-mineral layers with a mull humus (**Ah**) (Fig. 4 d);
3. Surficial and buried organo-mineral layers with the uniform yellowish–gray colour and mull-type humus formed due to the activity of earthworms, loamy sand, charcoal fragments are rare or absent, lower boundary is smooth and abrupt, with characteristic 0.2–0.7 cm spots and streaks created by the earthworm casts and tunnels (**Ap**) (Fig. 5, f);
4. Surficial and buried organo-mineral layers, sand to silt loam, with the dark –gray to medium-gray background colour dotted by numerous round and oval spots of lighter colors, 1–1.7 cm in diameter, (Fig. 5, b-e). Dark coloration is caused by the intimate mix of charcoal particles of various sizes with the mineral mass: numerous fragments of charcoal are well visible on the section walls, each sq cm of the layer containing at least one charcoal fragment (**Apyr**) (Fig. 4 a-f).
5. Surficial and buried organo-mineral sandy layers with uneven black to-cinder-gray coloration, consisting of the intermingled laminae and lenses of the powdered charcoal and mineral soil mass (Fig. 5, a). The type of bedding is consistent with the lateral transport of the materials in a hypersaturated flow (colluviation); the stratification is achieved due to the drastic difference in the particle density of mineral grains and charcoal (**EApyr**) (Fig. 4 a, b).

The last two types (4 and 5) both contained charcoal, but in Apyr charcoal fragments were intimately mixed with the mineral mass, and in **EApyr** they were stratified.

To differentiate these types of dark-coloured layers from the layers. We used a subordinate distinction ***pyr*** in order to reflect pyrogenic origin of these dark-coloured layers, in contrast to the dark-coloured products of biomass humification in Ah horizons.

Identifier **pyr** was proposed for designation of the soil horizons that contain a substantial amount of charcoal in > 2 mm fraction of the soil (Ponomarenko et al., 2018). Here we used the ***pyr*** designation for the horizons that originated from burning and gained their black coloration from charcoal, to denote the abundance of charcoal and the pyrogenic nature of the layer. The uniformly-coloured silt layers with a more homogeneous distribution of dispersed charcoal (3) were designated as

Fig. 4. Soils of the study sites: *Forest* (a, b) – note a consistent deposit BA bedded over Apyr and v-shaped intrusions of Apyr into underlying substrate, possibly caused by tillage implements; *Farmland* (c, d) – (c) an area of experimental swidden in the upper part of a slope, note an experimental swidden layer at the surface and an ancient swidden layer buried under the plough horizon and (d) a deep accumulative profile at the toe slope where two Apyr layers divided by a slope deposit are preserved beneath the plough horizon; *Buschland* (e, f) – (e) a profile preserved under the root collar part of pine (e), yellow arrow points in the direction of tree fall; and (f) a profile in the mid-part of slope, white line delineates traces of a large tap root of a tree that was pulled out and in-filled by the material of Apyr(1).

Apyr horizons. The layers with clusters and lenses of charcoal within the bleached sand matrix were designated as AeApyr horizons.

The Apyr horizon was bedded at the surface in the experimental slash-and-burn site and in the *Buschland* site; in other sites Apyr horizons were bedded at depth. When more than one Apyr horizon were encountered in the soil profiles, they were either clearly divided by deposits, or superposed on each other, slightly differing in the hues and in the intensity of the gray colour (Fig. 4).

The experimental slash-and-burn layer (Apyr(exp)) in the *ESAB* site appeared as a 3 to 9 cm -thick brownish-gray (10 YR 4/2) sandy loam layer with a clear, slightly undulated lower boundary(Figs. 4c and 5f). Numerous charcoal fragments, mainly of a sub-centimetre length, were visible on the section wall. The layer was compacted, with thin cracks extending down to 10 cm and charcoal fragments in the crack infill. The surface of Apyr in ESAB site was considerably even, repeating the generally even surface of the plough field. A thickness of Apyr increased in micro-depressions. In the *Buschland* site two Apyr were recorded (Fig. 4 f, one close to the surface and another at depth, appearing as dark-coloured silt loam layers 4 to 10 cm thick. The Apyr layer was described immediately under the root collar of the pine that was recruited on the abandoned swidden (Fig. 4e), i.e. exactly this layer was a surface layer at the time the site was involved in the SABC. The colour of the Apyr layer was dark-gray in the wet state, grading into a much lighter colour on drying (Table 2). Both the dark colour and drastic change in the colour value upon drying were associated with a considerable proportion of charcoal in the soil mass. Wet samples from Apyr had a specific sooty smell and took a much longer time to air-dry than samples from humus layers, presumably due to the high sorptive capacity of charcoal. The surficial Apyr layer in the documented swidden (*Buschland* site) and Apyr layers at depth in this site and in other sites had similar colour, texture, and the pattern of the lower boundary.

The common colour parameters characteristic of Apyr layers in our sites were a yellow-red hue (10 YR) and low values (dark coloration), with the chroma (saturation of colour) ranging within several units of the Munsell scale, from 10 YR 5/2 to 10 YR 5/4 in dry state.

The lower boundary of all Apyr layers but Apyr(exp) had a scalloped fringe formed by numerous finger-like tunnels and round chambers, 1 to 1.5 cm in diameter, spaced within several cm from each other (Fig. 5 b-e). The constructions are in-filled by the dark-coloured material of the Apyr layer and charcoal beneath the layer's lower boundary, and by the material of B horizons above the boundary, forming a transitional layer that consists of the bright mosaic of buff-coloured and gray spots. The depth of most constructions did not exceed 15 cm from the surface of Apyr. Another type of insect constructions, with a vertical central shaft, could be traced down to 30 cm from the surface of Apyr (*Forest* site). Such size, shape, depth, and density of constructions are typical for sweat bees, particularly of *Lasyoglossum* genus (Michener, 1974). Retallack (1984) described the following features as diagnostic for *Lasyoglossum* in paleontological record:

1) elongated brood cells, tapering near a short flaring entrance (“finger-like” appearance on a vertical section), diameter of cells up to 20 mm,
2) cells oriented subhorizontally, with their long axes slightly curved, convex down,

Fig. 5. Lower boundary of organo-mineral layers: (a) lenses of powdered charcoal and bleached mineral soil mass in EApyr, *Forest*; (b) traces of fossorial insects on the vertical and horizontal surfaces at the lower boundary of Apyr, *Buschland*; (c–e) traces of fossorial insects (digging bees and wasps) in swidden layers: Apyr(1) - *Farmland*, (d) Apyr(2) - *Farmland*, Apyr(2) - *Buschland*; (f) an even and abrupt boundary of Ap with traces of earthworms and a more gradual boundary of Apyr(exp).

3) cells arranged in flat-lying radial clusters connected through short lateral burrows to a central vertical burrow,
4) cells filled with different material than the encasing substrate.

Recent studies indicate that the sweat bees of *Lasyoglossum* genus are responsible for pollination of insect-pollinated crops in modern slash-and-burn sites in tropical regions (Landaverde-González et al., 2017), and the majority of insect-pollinated crops elsewhere (Kleijn et al., 2015). The constructions of digging bees are commonly associated with non-humified surfaces and outcrops, such as overgrazed dune sands, quarry walls, and soil clods of tree uprootings, whereas their presence in the dark-coloured/humus layers is rather unusual.

These trace fossils were not observed in the experimental slash-and-burn layer, possibly due to the loamy texture of the former plough layer that was affected by burning. The population of earthworms survived the experiment, and that too could have contributed to maintaining the high consistency of the surficial layer after burning. Though some earthworms are present in the *Buschland* site currently, their traces in the buried Apyr layers are not distinct.

Another feature of the lower boundary of Apyr was the presence of root traces (phyto-trace fossils). In the *Buschland* site a trace of pulled-out tree taproot, 15 cm in diameter, extended for 40 cm below the lower boundary of the swidden layer (Fig. 4, f). The root hollow was in-filled by the material of Apyr, charcoal fragments being noticeably larger in the hollow in-fill than in the Apyr layer. Smaller root moulds were recorded at the lower boundary of Apyr in the *Forest* site (Fig. 4, a).

Table 2
Some properties of soils in the historic swidden sites.

	Color	Corg, %	P, mg/100 g	Particle size, %					
				1–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	< 0.001
Forest									
EApyr, 0–3.5 cm	10 YR 4/2	1.4	0.85	33.53	52.68	5.97	1.25	4.44	2.14
Bh, 3.5–5.5 cm	10 YR 3/5	1.2	18.51	43.53	43.06	6.52	1.09	3.65	2.15
Apyr, 5.5–10.5 cm	10 YR 5/4	2.3[a]	13.49	39.61	48.66	6.13	1.05	3.14	1.41
Bs, 10.5–20 cm	10 YR 5/6	0.35	11.73	32.09	57.96	5.14	1.09	3.40	0.32
ESAB/Farmland									
Apyr (exp), 0–7 cm	10 YR 4/2	1.55	5.53	35.53	25.64	22.63	4.98	9.76	1.45
Ap(1), 6–45 cm	10 YR 5/4	0.60	3.51	31.89	39.34	14.63	5.31	7.66	1.18
Ap(2), 45–65 cm	10 YR 4/3	0.60	1.30	19.61	43.99	21.85	3.61	9.32	1.62
Apyr(1), 65–75 cm	10 YR 5/3	1.47	0.81	24.42	36.63	23.30	5.58	8.50	1.56
BA, 75–80 cm	10 YR 5/4	0.51	0.85	26.00	34.80	24.56	4.79	8.09	1.77
E > 92 cm	10 YR 7/3	0.17	0.91	15.58	36.60	28.42	6.81	11.25	1.35
Bushland									
ApyrE 7–12 cm	10 YR 4/3	1.85	1.04	36.28	30.06	21.40	2.42	6.56	3.28
Apyr(1) 12–19 cm	10 YR 5/3	2.28	0.81	32.55	36.97	17.63	3.92	5.79	3.14
Apyr(2) 25–32 cm	10 YR 5/4	2.21	0.89	35.19	35.14	18.67	2.57	5.34	3.10

[a] The layer contained 0.6% of $CaCO^3$.

The similarity of the Apyr layers in different sites/time periods and their similarity with the Apyr layer preserved under the root collar in the documented swidden site allows us to assume that these layers are associated with the slash-and-burn cultivation.

In our sites, formation of Apyr layers was followed by the downslope mass movement that resulted in their burial under deposits (BA). This process created complex soil profiles with one or more buried Apyr layers divided by deposits.

BA horizons were of a similar thickness, varying from 6 to 10 cm in *Buschland*, from 4 to 12 cm in *Forest*, and from 5 to 7 cm in *Farmland*. The deposits were uniformely coloured, with the colors similar to the colors of horizons underlying Apyr, but of a more grayish hue. Charcoal fragments were uniformly distributed within the layer, but in smaller quantities than in below-bedded Apyr.

The upper contact of Apyr layers with covering deposits is rather diffuse, lacking any fragments of buried surfaces (Fig. 4). Constructions of fossorial bees penetrated from Apyr layers into the lower part of the covering deposit, indicating that the surface was rapidly buried when bees still inhabited the Apyr.

In the *Forest* site, the covering deposit above a single buried Apyr layer has not been affected by pedoturbation and has well-defined boundaries, while in the *Bushland* site the BA deposit between Apyr(1) and Apyr(2) has traces of shallow tree uprooting in the form of cauldron-like structures with inverted stratigraphy (large, amorphously-shaped spots of various coloration in-filling the cauldrons). The latter marks a prolonged (> 40 yrs) reforestation stage.

While the surface of Apyr is very uneven, presumably following a natural unevenness/hummocky microrelief of the forest floor at the time of land clearance, the surface of the covering deposits appears more even. The thickness of the deposits is larger in micro-depressions and smaller in convex loci, forming a modern, fairly even surface of recent *Buschlands*. Still, the deposits are well pronounced even in convex loci, forming a continuous layer of approximately the same thickness (4–12 cm) as the below-bedded Apyr.

Generally, mass movement/colluviation does not occur under forest ecosystems and is associated with the phase of deforestation, such as land clearance and stand-replacement fires. According to descriptions of modern swiddens in the tropics, the SABC may trigger lateral transport of surficial materials, landslides, and rill erosion in mountainous areas, while European slash-and-burn experiments suggest that erosion caused by the SABC is insignificant/negligible (Eckmeyer et al 2007). If erosion did occur in our case, we would expect formation of rills in erosional loci and colluvial fan sediments in accumulative loci. Typical features of colluvial fan deposits are their local and uneven distribution within a site, heterogeneity of deposited materials, and presence of flow structures, such as lenses and laminae. However, in our sites the covering deposits have no stratification, they are mixed and form a continuous layer across the microrelief.

It appears that these deposits may be associated with a stage of forked ard ("scratch plough") tillage that took place sometime after the initial forest clearing, burning, and harvesting in the cycle of SABC. Such cultivation could create a continuous layer of material that was transported from convex loci downslope and redeposited, in-filling concave loci. Examination of horizontal sections at the contact of Apyr and BA would help to test this assumption.

4.2. Age of Apyr layers

The number and age of Apyr layers varied among the sites (Fig. 4, Table 3).

In the *Farmland* site, two Apyr layers were preserved under the plough layer. The profile consists of a basal Podzolic horizon (E), - pyrogenic layer Apyr(2) (5 to 7 cm thick), - destratified slope deposit BA (5 to 10 cm), - pyrogenic layer Apyr(1) (10 to 12 cm), - plough layer Ap (60 to 65 cm thick) (Fig. 4d).

The large thickness of Ap was accumulated due to the constant input of materials from the adjacent slope, but the accretion rate was changing over time, as the plough layer consisted of two parts differing in a colour and in charcoal content. The lower part of Ap (Ap(2), 45–65 cm) contained more charcoal than the upper part of Ap (Ap(1), 6–45) and had a higher silt content than both Ap(1) and Apyr(1). That indicates that one more burning event could possibly precede the establishment of the permanent field.

The earliest dated burning in *Farmland* occurred shortly after AD: 952 ± 40, according to the AMS-radiocarbon dating of spruce charcoal from the lowermost pyrogenic layer Apyr(2) (Table 3). Birch and spruce charcoal from the upper pyrogenic layer Apyr(1) yielded ages AD 1569 ± 49 and AD 1560 ± 53 correspondingly. Pine charcoal from the lower part of the plough layer, Ap(2), yielded C14 age 370 ± 23 BP. This date has several interceptions with the calibration curve: 501–427 (60.1%), 392–387 (1.1%), and 380–319 (34.2%), thus the permanent field could be established in the site as early as in the 16th century and as late as 17th century AD. This age estimate does not take into account the absolute age of trees at the moment of land clearance, assuming that the permanent field was established in the slash- and -burn fallow where the trees were young.

Table 3
Ages of the historical swidden layers.

Site, layer	Lab ID	Material	14C yr BP	cal BP	cal AD/BC
Farmland, Ap(2)	UOC-6406	*Pinus* charcoal	370 ± 23	501–427 (60.1%) 392–387 (1.1%) 380–319 (34.2%)	AD: 1534 ± 66
Farmland, Apyr(1)	UOC-5067	*Picea* charcoal	333 ± 20	466–310(95.4%)	AD: 1560 ± 53
Farmland, Apyr(1)	UOC-5066	*Betula* charcoal	318 ± 21	459–349(75.3%) 336–306(20.1%)	AD: 1569 ± 49
Farmland, Apyr(2)	UOC-5866	*Picea* charcoal	1075 ± 26	1055-1022 (22.9%) 1010-931 (72.5%)	AD: 952 ± 40
Bushland, Apyr(2)	UOC-6407	*Betula* charcoal	864 ± 24	901–867 (8.2%) 825–815 (1.2%) 800–725 (84.3%) 719–705 (1.7%)	AD: 1179 ± 23
Forest, Apyr	UOC-5068	*Pinus* charcoal	235 ± 20	308–281(59.2%) 170–151(33.2%)	AD: 1715 ± 68

In the *Forest* site, a single Apyr layer was detected (Fig. 4a and b). The profile consists of a basal Bs horizon (10 to 20 cm thick), - Apyr (5.5 to 7.5 cm), - BA(4 to 8 cm) - Bh (2 to 3 cm), - EApyr (0.5 to 3.5 cm), - O (8 to 10 cm).

Charcoal fragments were found in AeApyr, Apyr, and (much fewer) in Bs.

The age of Apyr in the *Forest* site is dated by the beginning of 18th century, AD: 1715 ± 68. In this site, an old-growth forest could be cleared for a swidden, therefore the land clearance could take place even later in time.

The Apyr layer is buried under a deposit BA in this site (Fig. 4a and b). A new micro-profile of a Podzolic soil with a 1.5 to 3 cm-thick bleached pyrogenic horizon (AeApyr) and intensely-coloured Bh horizon was developed on this deposit.

In the *Buschland* site, two buried Apyr layers divided by a deposit BA were recorded in test pits (Fig. 4e and f).

In the soil profile preserved under the root collar of ~120-yr old pine, a surficial layer Apyr(1) and buried layer Apyr(2) were divided by a deposit BA. The surficial layer was 12 cm thick, with spots of in-filled insect burrows visible throughout the horizon. The layer is thicker than Apyr in other test pits, and was even thicker initially, taking into account soil compaction beneath a root collar. Some differences were noticeable between the upper and lower (7–12 cm) parts of the layer, the latter containing more charcoal fragments and had a denser network of insect burrows.

In two other test pits, located at the mid-slope and at the toe slope the stratigraphy was more complex. A surficial horizon ApyrE was dark-coloured (10 YR 4/1) while in the wet state and changing colour drastically upon drying due to a large proportion of bleached sand grains. The layer is similar to the EApyr layer in the presence of both charred mass and bleached sand grains, but here the bleached material is intimately mixed with the matrix.

The soil profile in both test pits consisted of a basal Bs horizon (10 to 20 cm thick), –Apyr(2) (4 to 9 cm thick) –BA (4 to 7 cm) – Apyr (1) (3 to 7 cm) — ApyrE (9 to 12 cm thick) – O (0 + 3 cm).

The upper part of the soil profile was pedoturbated in both test pits: at the toe slope section the surface layer was more heavily mixed by wild boars for depth up to 12 cm, while in the upper part of the slope surficial layers were affected by tree uprooting even deeper. In these pits, constructions of fossorial insects were visible only under the ApyrE layer. It appears that the surficial horizon ApyrE is a result of pedoturbation that affected the most recent swidden layer. The unusually large thickness of surficial Apyr under the root collar of pine may attest for merging together of two subsequent swidden layers. Birch charcoal from the lower pyrogenic layer Apyr(2) yielded age AD: 1179 ± 23.

According to this date, three stages of land clearance took place in the site in the last ~800 years, with a long-term reforestation of the site at least between the first two clearings.

4.3. Soil properties

Some basic soil properties of studied layers are presented in Table 2.

All sites are located on sandy (loamy sand to sandy loam) soils, as indicated by the grain size analysis. The Apyr layers are characterized

Table 4
Morphometry of charcoal fragments.

Site, layer	Length, mm Average	Length, mm Standard Deviation	Width, mm Average	Width, mm Standard Deviation	W/L, Average	W/L, Standard Deviation
ESAB/Farmland						
Apyr(exp)	4.7	1.9	2.3	1.0	0.5	0.25
Ap(1)	3.1	1.1	1.9	0.8	0.6	0.21
Apyr(1)	4.1	1.4	2.8	1.5	0.7	0.25
BA	2.8	1.6	1.8	0.9	0.7	0.29
Apyr(2)	2.5	0.7	1.6	0.6	0.7	0.28
Forest						
ApyrE dead wood	4.7	1.9	3.0	1.5	0.7	0.22
ApyrE	1. 9	0.9	1.4	0.6	0.8	0.25
Bh + BA	3.7	1.5	2.1	0.9	0.7	0.28
Apyr	5.0	1.7	3.0	1.0	0.6	0.21
Bs	3.4	1.0	2.2	0.8	0.7	0.26
Bushland						
ApyrE, 7–12 cm	4.3	1.7	2.7	1.2	0.7	0.23
Apyr(1), 12–19 cm	3.9	2.4	2.7	1.7	0.7	0.29
Apyr(2),25–32 cm	4	1.5	2.2	1.0	0.6	0.26

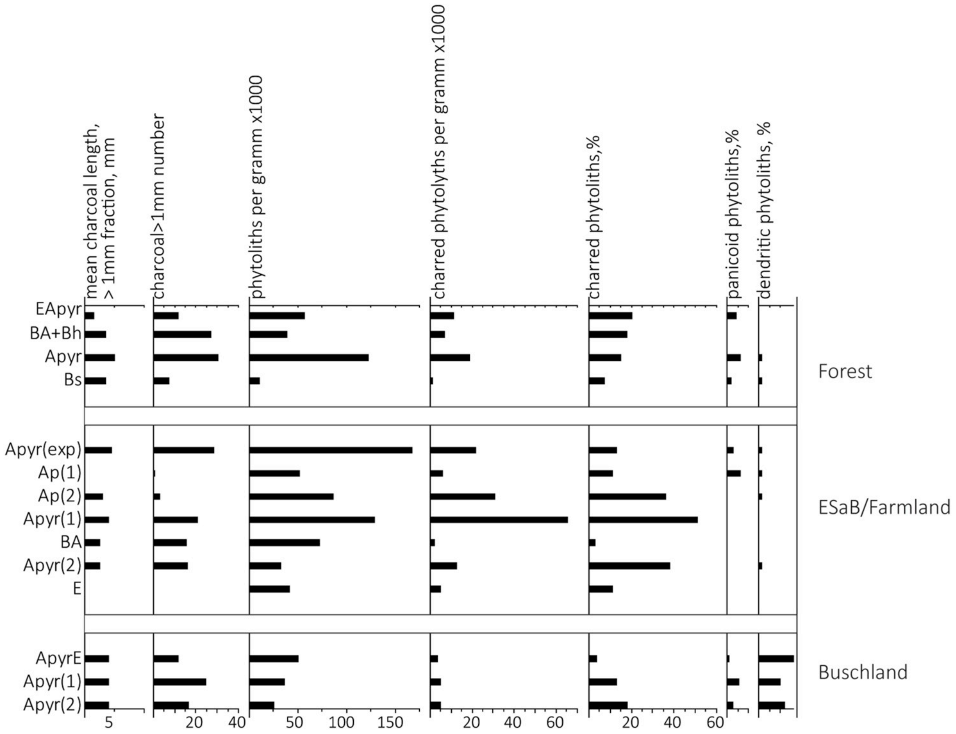

Fig. 6. Distribution of charcoal and phytoliths in the soil profile.

by a remarkably high carbon content, varying from 1.45 to 2.3%. The carbon content of Apyr layers is 0.8–1.1% higher than that of the organo-mineral horizons below and above, including the plough layers, and similar to the carbon content of EApyr. The difference in the carbon content can be therefore attributed to high charcoal content of the pyrogenic layers. The phosphorus was analyzed as an indicator of dung and manure input in the soil (Holliday and Gartner, 2007). The phosphorus content was higher in the surficial parts of plough layers than in the swiddens in *ESAB* and *Buschland* sites, consistent with the application of either dung or manure.

4.4. Charcoal content

Size of charcoal fragments in > 1 mm fraction of Apyr layers had the median varying from 3.9 to 5 mm, standard deviation (SD) 1.3 to 1.7 (0.34%) (Table 4). The average width to length ratio was very stable for charcoal fragments from all Apyr layers, ranging from 0.6 to 0.7. These parameters were similar for all Apyr layers and for EApyr of *Forest* (0.7–0.8) regardless of the taxa charred. Such stability of the "pebbly" shape may indicate rounding of charcoal fragments during their lateral transport (Ponomarenko and Anderson, 2013).

The size of charcoal in BA layers superposed on the Apyr (redeposited material of Apyr) is slightly smaller than in the Apyr, with the median varying from 2.8 to 3.7 mm.

The charcoal size was noticeably smaller in the layer formed by the forest fire (EApyr, *Forest* site), with the average length of 1.9 mm. In contrast to the charcoal size, an average length of dead wood fragments in this layer was much greater than that of charcoal, averaging 4.7 mm. However, only one fire layer was examined; a greater number of samples is needed for the reliable comparison of the charcoal morphometry in the two types of horizons.

4.5. Charcoal concentrations in the Apyr layers

Not only the length of charcoal fragments, but also their concentration in the soil mass, measured as a number of fragments per gram (weight %) peaked in the swidden layers (Fig. 6). The number of > 1 mm-sized charcoal fragments varied among the Apyr layers from 0.8 to 1 per gram of air-dried soil and from 16 to 30 per gram of > 1 mm fraction of soil.

Charcoal concentrations in the BA deposits were only slightly lower than in the swiddens, whereas EApyr appeared to have lower concentrations. However, the number of samples is not sufficient for definitive conclusions. Finally, the concentrations were minimal in the plough layers, varying for the two parts of plough layer from 0.4 per gram of air-dried soil in Ap(2) to 0.1 in Ap(1) (8 and 2 per gram of > 1 mm fraction of soil correspondingly).

4.6. Surface of charcoal fragments

Surfaces of all charcoal fragments in Apyr layers had a characteristic 'battered' appearance due to the extensive cinder-gray silt coating (Fig. 7, a). The silt coating was equally thick on the fragments from the recent experimental burn and from older Apyr layers. The coating had the same colour as the soil mass, and the mud-coated charcoal fragments appeared as soil aggregates with a charcoal nucleus.

The same uniform silt coating was observed in BA deposits bedded over the swidden layers and on charcoal fragments from the lower part of the plough layer (Ap(2), *Farmland*), probably inherited from the land clearance stage.

In the *Farmland* and *Forest* site, located at the toe slope, iron deposition on the surface of the mud-coated charcoal was observed in the BA layers covering the Apyr layers (Fig. 7, b-d). The iron coating was more pronounced in the *Forest* site. Here the appearance of the mud-coated charcoal with the secondary deposition of iron oxides over the mud coating is similar to that of charcoal-cored iron-manganese concretions (Ponomarenko and Anderson, 2013), but the shape of the fragments is less rounded and they lack the hardness of the concretions, both due to the insufficient degree of iron-incrustation.

In the "wildfire" layer EApyr of the *Forest* site, surfaces of charcoal fragments were free of the silt coating, and mixed with a proportion of transparent, bleached grains of quartz sand.

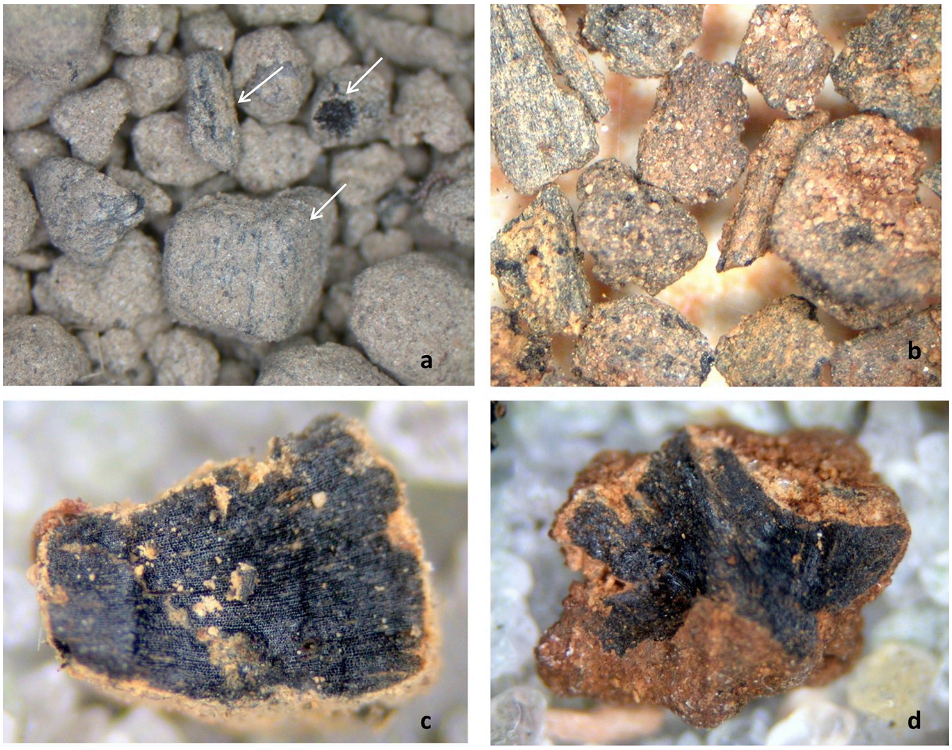

Fig. 7. Rounded and mud-coated charcoal in a swidden layer, *Buschland* (a); charcoal-cored iron-impregnated aggregates with in a lowland setting, Apyr, *Forest* (b–d).

4.7. Composition of > 1 mm soil fraction

Composition of macrofossils in > 1 mm size fraction of the soil is presented in Table 5 and on Fig. 8.

The assemblages from Apyr layers contained a considerable proportion of charred needles of conifers and buds of deciduous trees, with charred spruce needles contributing almost 40% in Apyr(2) (*Farmland*). All Apyr but the lower pyrogenic layer in *Buschland* (Apyr(2)) contained *Chenopodiaceae* seeds (not charred). The proportion of *Chenopodiaceae* seeds was maximal (~36%) in the experimental swidden (currently used as a pasture) and fairly high (~9%) in the lower Apyr(2) in the *Farmland* site. The proportion of bark was low, ~7% in the experimental swidden and from 1 to 4% in the other Apyr. The insect parts and coprolites were either solitary (1% and less) or absent.

Composition of macrofossils in the pyrogenic layer ApyrE and the Bs horizon was drastically different. The proportion of bark was ~23% in ApyrE and 12% in Bs, the insect body parts and coprolites contributed 11 and 3% respectively, foliage and weed seeds were absent.

The presence (and the high proportion) of charred foliage in Apyr layers is expected if the trees (along with their foliage) were on the ground at the time of burning as described for the SABC technology of burning (Petrov, 1968).

The presence of zoochoric *Chenopodiaceae* seeds that are not charred, but are found in the same assemblage as the charred wood and needles may be indicative of using the site as the forest pasture at the fallow stage.

A combination of the large proportion of bark and numerous body parts of insects in the assemblages from EApyr and Bs is consistent with the processes that take place after ground fires and surface fires in fire-sensitive ecosystems. Mainly bark is affected by the fires, with the trunk wood and foliage being intact. If fire-sensitive species are present either in the canopy or in the understorey, the trees die-off shedding charred/scorched bark and hosting a suite of insects, many of them saprotrophic (e.g. Whitehouse 2000).

4.8. Species composition of charcoal assemblages in pyrogenic layers

The experimental swidden (Apyr(exp)) provided an opportunity to estimate representation of charred taxa in the charcoal assemblages, as an approximate amount of fuel by species was known. We have compared the biomass of the firewood by species with the percentage of the same species in the charcoal assemblages calculated as a percentage of charcoal fragments of each species of the total number of identified fragments (Table 1). The charring coefficient was calculated as a ratio of charcoal percentage to percentage of the same species in the firewood.

The taxa recorded in the charcoal assemblage were *Pinus* (pine), *Picea* (spruce), *Betula* (birch), *Alnus* (alder), and *Salix* (willow).

Table 5
Composition of macrofossils, % of the total number of biogenic components in the soil size fraction > 1 mm.

	Buschland			Farmland			Forest		
	ApyrE	Apyr(1)	Apyr(2)	Apyr(exp)	Apyr(1)	Apyr(2)	Apyr	ApyrE	Bs
Chenopodiaceae seeds, not charred	0.7	3.7		35.5	1	8.6	0	0	0
Insect body parts and coprolites, not charred				1		0.8		11.4	3
Bark, charred and partially charred	2.9	3.5	4.3	6.8	1.6	1	7.8	22.8	12
Foliage (needles, leafs, and buds), charred	3.4	7.4	0.8	6.8	5.7	39	0	0	0

Fig. 8. Components of soil large fractions: insect parts (a) and bark fragments (b), EApyr (*Forest*); *Chenopodium* sp. seeds (c) and charred spruce needles, Apyr(2), *Farmlands*.

Percentage of deciduous species and pine in the charcoal assemblage was remarkably close to the estimated percentage of their biomass in the firewood, with the charring coefficient ranging from 0.9 for alder and 1.1 for willow to 1.4 for birch. Given the low precision of initial measurements, the first two coefficients are expected to fall within a possible error, while birch appears significantly overrepresented in the charcoal assemblage. Pine was slightly underrepresented (0.7), while spruce was absent among charcoal fragments (n = 190) and represented only by charred needles.

Charring experiments conducted by archaeologists indicate that the outcome of the process depends on the size of fuel and its condition (wet vs. dry) rather than the species burned (Théry-Parisot et al., 2010). However, testing of fire-resistance in standard slabs of various wood species attested a negative correlation between the intensity and rate of ashing and wood density, resulting in a faster and deeper ashing of coniferous wood (Braadbaart and Poole, 2008; Shaffer, 1966). Since the experimental burning aimed to reproduce the technology of SABC, our rough estimations of the charring coefficients were applied for the interpretation of charcoal assemblages from historical swiddens.

The taxa recorded in the charcoal assemblages of historical Apyr layers are very similar to that of the experimental burning: the majority of fragments were pine, spruce, birch, and alder charcoal, with a few fragments of oak and linden. The proportions of each species, and especially of pine, differed considerably in the layers of various ages (Fig. 9):

- The charcoal assemblage of the oldest Apyr (Apyr(2), *Farmland*) dated by the end of 10thcentury is dominated by spruce, with a proportion of birch and alder. Assuming the high rate of ashing, that may reflect burning a dense spruce stand.
- During the next cycle of burning that occurred in the same site in mid-16th century (Apyr(1), *Farmland*), the charcoal originated entirely of birch wood.

Charcoal assemblage from the above-bedded layer Ap(2) (*Farmland)* had almost equal proportions of pine and birch, with the proportion of alder increasing compared to the older assemblages. Pine appeared in the charcoal assemblages for the first time in this layer. The difference between the species composition of charcoal assemblages in Apyr(1) and Ap(2) may attest for the third burning event, closely preceding the establishment of the permanent field, though radiocarbon dating of charcoal in both layers yielded approximately the same age. In the Apyr layer of the *Forest* site, dated by the early 18th century, the charcoal assemblage was dominated by pine and spruce, with a proportion of birch.

In the *Buschland* site, pyrogenic layers contained charcoal of the same taxa (pine, spruce, birch, and alder), but their proportions varied among the layers.

- Spruce charcoal was dominant in the oldest swidden layer (Apyr(2)) dated by 12th century AD;
- During the following clearance (Apyr(1)) the proportion of spruce charcoal decreased, and the proportion of birch charcoal increased twofold.

The species composition of the BA layers superposed on the Apyr layers closely resembled that of the Apyr layers, consistent with their origin through the lateral transport and redeposition of the Apyr material. The smaller proportion of spruce charcoal (probably due to its fragility) in BA deposits can be noted.

A charcoal assemblage of the upper pyrogenic layer EApyr in the *Forest* site consisted entirely of coniferous charcoal, with charcoal of pine being twice more abundant than the spruce charcoal. Charcoal assemblages from other layers in this soil section are also lacking deciduous charcoal. It appears that the coniferous forest was cleared here for SABC just once, not becoming a part of the *Buschland* rotation cycle.

Chronological ordination of the charcoal assemblages allows for noticing the following tendency in the species composition:

- 10th century: spruce dominance (Apyr(2) *Farmland*)
- 12th – 16th century: mixed forest dominated by birch and alder with a proportion of spruce (Apyr(1), *Farmland*), or spruce and pine (Apyr(2), *Buschland*)
- 17th-19th centuries: mixed forest,– increase in the proportions of

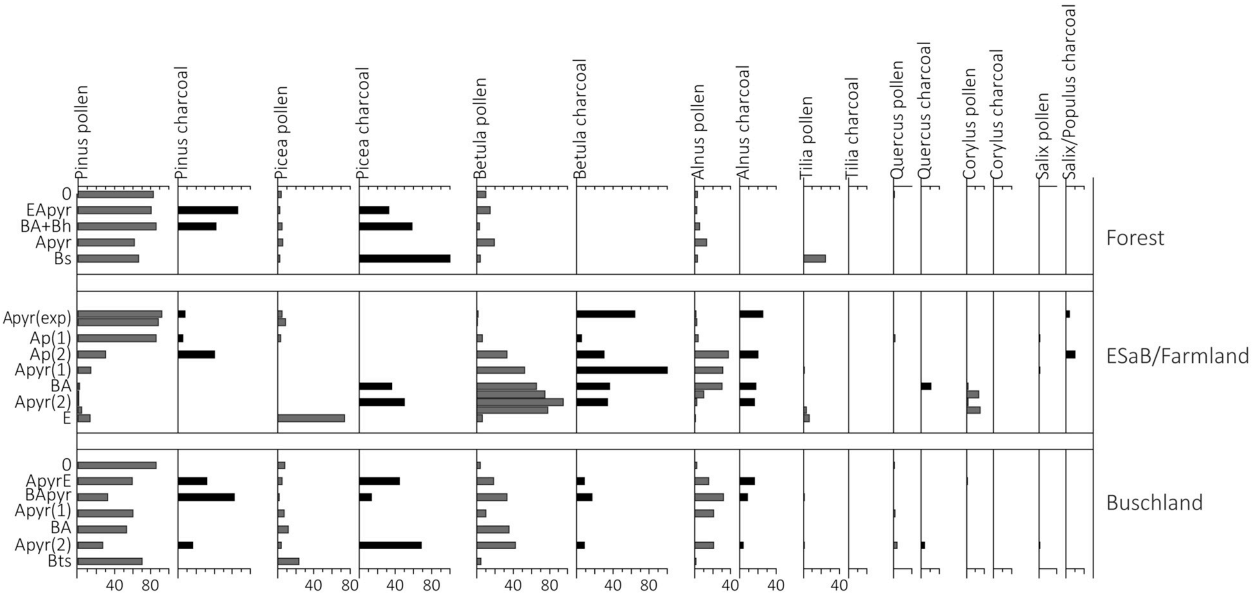

Fig. 9. Distribution of arboreal taxa in pollen spectra (gray) and charcoal assemblages (black). Pollen percentage of each taxon is calculated as a percentage of the arboreal taxa only.

pine (Apyr, *Forest*), or pine and alder (Ap(2), *Farmland*, Apyr(1), *Buschland*)

4.9. Ash and phytoliths

The insoluble fraction of ash, - the phytoliths, was a ubiquitous component of the Apyr layers (Fig. 6). In the profiles analyzed, the phytolith concentration peaked in the pyrogenic layers. Concentrations of phytoliths (their numbers per gram of soil) in Apyr were very high, reaching 200 000 per gram in the experimental (most recent) swidden. The concentration of phytoliths in older Apyr layers varied from 280 thousands per gram in Apyr layers of *Buschland* to 50 thousands per gram in the oldest swidden (Apyr(2)) of the *Farmland* site. Such concentrations may be sufficient for increasing the silt content of the pyrogenic layers, but this tendency is noticeable only in some of Apyr; a greater number of samples has to be analyzed to confirm this observation. The percentage of charred phytoliths clearly peaked in the pyrogenic layers, contributing from 20 to 50% of the total phytolith content. Interestingly, the proportion of charred phytoliths in the experimental swidden was only slightly higher than in the underlying plough layer. Both the total concentration and the proportion of charred phytolith were several times higher in Apyr than in other layers, including both the anthropogenic plough layers, BA, and a “natural” soil horizon EApyr.

Distributions of both the total concentration of phytoliths and the percentage of charred phytoliths closely resembled that of charcoal concentrations in the soil profile.

Documented swidden layers (*Bushland*), the experimental swidden (*ESAB*), and the plough layers (Ap(1), Ap(2), *Farmland*) contained dendritic phytoliths providing an evidence of *in situ* cultivation of cereals.

Either dendritic phytoliths of cereals alone, or these and fragments of cereal glumes and paleas were found in Apyr of all other sites/time periods, confirming association of these layers with the swidden cultivation.

Dendritic phytoliths of cereals were absent in ApyrE layer (*Forest*), supporting the assumption that this layer is associated with the forest fire. Dendritic phytoliths in the surficial ApyrE layer in Buschland site indicate that the material of this layer was affected by cultivation.

Of special interest is a steady presence and a considerable proportion of panicoid phytoliths, typical for *Panicum* spp and *Setaria* spp in most Apyr layers and in the plough layer of *Farmlands*. The millet has not been mentioned among crops in the area since 16th century (Ligi, 1968)), though millets were found in archaeological sites of Iron Age in Lithuania (Grikpėdis and Motuzaite-Matuzeviciute 2017). Therefore, it is possible that the panicoid phytoliths originated from *Setaria,* possibly *Setaria viridis* - a local annual plant associated with disturbed habitats. The panicoid phytoliths were also found in EApyr of Forest site.

4.10. Pollen

All studied soil layers contained well-preserved pollen. Despite the possibility of a partial mixing of pollen from different depths by bioturbation (e.g., earthworms), the pollen spectra of subsequent layers formed distinct series, allowing for the reconstruction of temporal dynamics of the vegetation cover (Fig. 10).

Pollen spectra of surface soil samples were similar in *Forest*, *Buschland*, and *ESaB* sites, containing mainly *Pinus* pollen (70–90%) with a proportion of other taxa, both forest and anthropogenic.

The plough horizons Ap(1) and Ap(2) in the *Farmland* site had the minimal proportion of arboreal taxa and the maximum proportion of the components brought in with either dung or manure, e.i. *Poacea* and *Cerealia*, meadow taxa, weeds and anthropochores, and spherulites. Both layers contained spores of *Riccia* (*R. glauca*) indicative of plough land (Vellak et al., 2015; Porley, 2001; Andriušaitytė and Jukonienė, 2013).

Pollen spectra of Apyr horizons from all sites/time periods were dominated by the taxa that could be termed “*Buschland*” taxa: *Betula* and *Alnus* were the dominant tree genera, common were *Pteridium* and *Lycopodium*, and taxa indicative of fires, such as *Onagraceae* pollen and *Marchantia* spores.

Calluna pollen was present in most layers in the forest sites (*Forest* and *Buschland*); but its proportion was noticeably lower in the Apyr layers compared to the EApyr layer associated with the forest fire (*Forest*) and the BA deposits dividing swidden layers (*Buschland*).

In the *Buschland* site, the Apyr layers with *Betula-Alnus-Poaceae-Cerealia* –[*Onagraceae*] pollen and *Marshantia* spores were alternated with the BA deposits containing *Pinus-Picea* –*Calluna* pollen. This sequence is very similar to the pollen sequences documented in palynological spectra of Karula lakes (Poska et al., 2017). In our case, the zones of *Betula-Alnus-Poaceae-Cerealia* –[*Onagraceae*] pollen and *Marshantia* spores are clearly associated with the Apyr layers, consistent

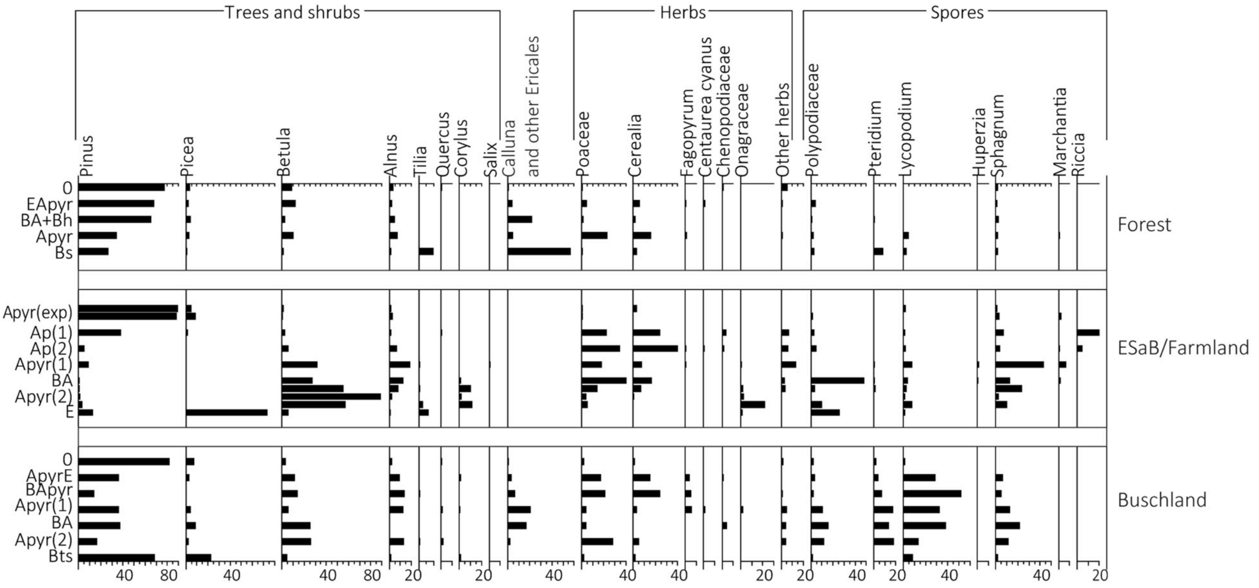

Fig. 10. Soil pollen and spores. The pollen of each taxon is calculated as a percentage of total pollen, the spores as a percentage of the sum of pollen and spores.

with their use in the cycle of swidden cultivation. Accumulation of *Pinus- Picea – Calluna* pollen in BA deposits corresponds with a long-term reforestation stage. The abandoned plough layer serves as a parent material for the formation of a new forest soil (e.g., dwarf Podzol in the *Forest* site), accumulating pollen of forest taxa.

Beside the forest taxa, some Apyr layers contained a proportion of crop and weed taxa, e.g. *Cerealia*, *Fagopyrum*, and *Centaurea cyanus* pollen.

The highest percentage of the meadow and crop taxa, *Poacea* and *Cerealia* pollen was found in the plough layers (Ap(1) and Ap(2), *Farmland*). However, the proportion of the *Poacea* and *Cerealia* pollen was comparably high (40% of the pollen spectra) in Apyr layers of 17th to 19th centuries, typical for the input of dung during cattle grazing (Ejarque et al., 2011). In the oldest swidden layer Apyr(2) (*Farmland*) dated by the 10th cent AD, *Poacea* contributed less than 5% of the pollen spectrum, and *Cerealia* pollen was absent. Similarly to the ancient swidden, the surface soil sample in the experimental site contained only several percents of *Cerealia* pollen, consistent with the pollen spectra represented in Tauber traps (Jääts et al., 2011). However, the proportion of *Cerealia* pollen was much lower in the experimental swidden than in the historical swiddens: the pollen spectrum was dominated by *Pinus* pollen. The experimental swidden was set within a large open farmland, more than 1 km in diameter. The soil surface of such field accumulates pollen similarly to a lake, reflecting regional palynological signal. This signal is drastically different from the local pollen signals accumulated in the early swiddens that appeared as small openings in the forest. Therefore, pollen spectra of the experimental swidden cannot be used as a reference for early swiddens.

The basal layer of the *Farmland* soil section (10th cent AD) was the stratum with the minimal evidence for the anthropogenic utilization of the landscape. The pollen spectrum of this layer was almost entirely composed by shade-tolerant arboreal taxa - *Picea* and *Tilia*.

The analyzed pollen spectra reflect the following dynamics of the ecosystem and land use:

- *Picea-Tilia* late-successional forest (10th century),
- Clearing the old-growth forest in the SABC cycle;
- Appearance of secondary *Betula-Alnus-Picea-[Tilia]* forests marking the forest fallow stage of SABC (12thcentury);
- Alternation of *Betula-Alnus*-dominated ecosystems with the *Picea-Pinus-Calluna* –dominated ecosystems, reflecting the alternation of clearing and reforestation stages (12th-17th century);
- *Pinus-Picea* ecosystems (19th century-modern). Formation of pine-dominated tree stands - pine becomes a dominant pollen producer in the area.

4.11. Pollen-charcoal correlation

Arboreal taxa recorded in the charcoal assemblages of swidden layers and the taxa recorded in the pollen spectra of the underlying layers have similar, but lagged distributions within the soil profile (Fig. 8). The arboreal taxa represented in the pollen spectra of the deposits dividing the subsequent swidden layers (BA) appear in the charcoal assemblages at the next stage of the land clearance. In the other words, pollen spectra reflect the species present contemporary to the time of the surface burial, whereas the charcoal assemblages reflect the species composition of the previous stage.

5. Conclusion

Soils of swidden sites contained one or more pyrogenic layers buried under slope deposits. Pyrogenic layers were identified as swidden layers based on (1) high numbers of > 1 mm charcoal fragments, uniformly distributed within the layer, (2) presence of charred foliage and a low proportion of bark in charcoal assemblages, (3) high concentrations of phytoliths with the large proportion of charred phytoliths, (4) presence of phytoliths of cultivars, and (5) presence of local pyrogenic indicators (*Onagraceae, Lycopodium, Marshantia*), cultivars (*Cerealia, Fagopyrum*), and weeds (*Centaurea cyanus*) in pollen spectra. Large fractions of swidden layers contained *Chenopodiacea* seeds, indicative of using swiddens for grazing at the fallow stage. Each of the analyses has its limitations, but together they allow for reliable identification of swidden layers. Morphological indicators of swiddens can be erased by pedoturbation, but even in this case the signature of swidden can be preserved in the form of high charcoal concentrations, phytolths of cultivars, and “swidden taxa” in pollen spectra.

From one to three swidden layers were recorded in our study sites, dated between 10th and 19th century AD. The slope deposits dividing swidden layers in our sites appear to be formed as a result of ard tillage of the swiddens. Tillage levelled the originally uneven surface of the forest floor, creating very short-lived plough layers. These layers marked a final stage of site utilization for SABC, followed either by the abandonment and reforestation of swiddens or by the establishment of a permanent field. The deposits (1) have the same species composition of charcoal assemblages and fuel fractions as the below-bedded swidden layers, but lower concentrations of charcoal; (2) phytoliths of cultivars are either present in lower numbers than in swidden layers or absent, and (3) pollen spectra are dominated by *Pinus, Picea*, and *Calluna*.

Acknowledgements

The research was partially funded by the Moscow State University, project № AAAA-A16-116021660037-7.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quaint.2018.10.016.

References

Alenius, T., Mikkola, E., Ojala, A.E.K., 2008. History of agriculture in Mikkeli Orijärvi, eastern Finland as reflected by palynological and archaeological data. Veg. Hist. Archaeobotany 17 (2), 171–183.

Andriušaitytė, D., Jukonienė, I., 2013. Patterns of bryophyte diversity in arable fields of Lithuania. Acta Soc. Bot. Pol. 82 (1), 57–65.

Barefoot, A.C., Hankins, F.W., 1982. Identification of Modern and Tertiary Woods. Oxford University Press.

Benkova, V., Schweingruber, F., 2004. Anatomy of Russian woods: an Atlas for the identification of trees, shrubs, dwarf shrubs and woody Lianas from Russia. Bern: Haupt. Bronk Ramsey, C. 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51 (1), 337–360.

Blinnikov, M.S., 2013. Phytoliths. In: second ed. In: Elias, S., Mock, C. (Eds.), Encyclopedia of Quaternary Science, vol. 3. Elsevier, Amsterdam, pp. 582–592.

Braadbaart, F., Poole, I., 2008. Morphological, chemical and physical changes during charcoalification of wood and its relevance to archaeological contexts. J. Archaeol. Sci. 35, 2434–2445.

Bradshaw, R.H.W., Tolonen, K., Tolonen, M., 1997. Holocene records of fire from the boreal and temperate zones of Europe. In: Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B.J. (Eds.), Sediment Records of Biomass Burning and Global Change. vols. 347–365 Springer, Berlin.

Carcaillet, C., 2001. Are Holocene wood-charcoal fragments stratified in alpine and subalpine soils? Evidence from the Alps based on AMS 14C dates. Holocene 11 (2), 231–242.

Conklin, H.C., 1961. The study of shifting cultivation. Curr. Anthropol. 2 (1), 27–61.

De Vernal, A., Henry, M., Bilodeau, G., 2010. Micropaleontological preparation techniques and analyses. Les Cahiers du GEOTOP 3. http://www.geotop.ca/.

Dimbleby, G., 1985. The Palynology of Archaeological Sites. Academic Press, London.

Dutoit, T., Thinon, M., Talon, B., Buisson, B., Alard, D., 2009. Sampling soil wood charcoals at a high spatial resolution: a new methodology to investigate the origin of grassland plant communities. J. Veg. Sci. 20 (2), 349–358.

Eckmeier, E., Gerlach, R., Skjemstad, J.O., Ehrmann, O., 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.

Ejarque, A., Miras, Y., Riera, S., 2011. Pollen and non-pollen palynomorph indicators of vegetation and highland grazing activities obtained from modern surface and dung datasets in the eastern Pyrenees. Review of Paleobotany and Palynology 167, 123–139.

Etverk, I., 1974. Metsa õpitakse tundma ja kasutama [Forest had been learned to know and use]. In: Valk, U., Eilart, J. (Eds.), Eesti Metsad [Estonian Forests]. Valgus, Tallinn, pp. 40–60.

GOST 54650-2011 Soils. Determination of Mobile Phosphorus and Potassium Compounds by Kirsanov Method Modified by CINAO.

Grikpėdis, M., Matuzeviciute, G.M., 2017. A review of the earliest evidence of agriculture in Lithuania and the earliest direct AMS date on cereal. Eur. J. Archaeol. https://doi.org/10.1017/eaa.2017.36.

Holliday, V.T., Gartner, W.G., 2007. Methods of soil P analysis in archaeology. J. Archaeol. Sci. 34, 301–333.

Jääts, L., Kihno, K., Tomson, P., Konsa, M., 2010. Tracing fire cultivation in Estonia. For. Stud. 53, 53–65.

Jääts, L., Konsa, M., Kihno, K., Tomson, P., 2011. Fire cultivation in Estonian cultural landscapes. In: Peil, T., Lang, V., Kull, K. (Eds.), The Space of Culture - the Place of Nature in Estonia and beyond. Tartu Universtity Publishers, Tartu, pp. 165–180.

Kachinskii, N.A., 1965. Механический И Микроагрегатный Состав И Методы Его Изучения [Mechanical and Microaggregate Composition and Methods of its Study]. AN SSSR, Moscow.

Karukäpp, 1974. Karula kõrgustiku reljeefist. [About the relief of Karula Upland]. In: Eesti Geograafia Seltsi Aastaraamat. Valgus, Tallinn, pp. 36–51.

Kleijn, D., Winfree, R., Bartomeus, I., et al., 2015. Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. Nat. Commun. 6, 8.

Lageras, P., 1996. Vegetation and Land-use in Smaland Uplands, Southern Sweden, in the Last 6,000 Years. LUNDQUA Thesis. vol. 36.

Landaverde-González, P., Quezada-Euán, J.J.G., Theodorou, P., et al., 2017. Sweat bees on hot chillies: provision of pollination services by native bees in traditional slash-and-burn agriculture in the Yucatán Peninsula of tropical Mexico. J Appl. Ecol. 54 (6), 1814–1824.

Lavento, M., 2012. Cultivation among hunter-gatherers in Finland – evidence of activated connections? In: A Linguistic Map of Prehistoric Northern Europe. Suomalais-ugrilaisen Seuran Toimituksia, vol. 266. Mémoires de la Société Finno-Ougrienne, Helsinki, pp. 1–40.

Ligi, H., 1963. Põllumajanduslik Maakasutus Eestis XVI–xvii Sajandil [Agricultural Land Use in Estonia in XVI–xvii Century]. Eesti NSV Teaduste Akadeemia Ajaloo Instituut, Tallinn.

Ligi, H., 1968. Talupoegade Koormised 13 Sajandist 19. Sajandi Alguseni. [Taxes of Peasants from 13th Century to Beginning of 19th Century]. Eesti Raamat, Tallinn.

Lihwlandi-ma tallorahva Seädus, 1820. Essimenne-kolmas Jaggu [Agrarian Law of the Livonian Governorate. First-third Section]. (Tartu).

Meikar, T., Uri, V., 2000. Võsamaade majandamisest Eestis [Managing the bushlands in Estonia]. In: In: Meikar, T., Etverk, I. (Eds.), Eesti Metsad Ja Metsandus Aastatuhande Vahetusel, vol. 11. Akadeemilise Metsaseltsi Toimetised, Tartu, pp. 103–120.

Michener, C.D., 1974. The Social Behaviour of the Bees, first ed.. Harvard University Press, Cambridge, MA, USA.

Petrov, V.P., 1968. Подсечное Земледелие [Slash-and-burn Cultivation]. Naukova Dumka, Moscow-Kiev.

Piperno, D., 2006. Phytoliths: a Comprehensive Guide for Archaeologists and Paleoecologists. AltaMira Press, Lanham, New York, Toronto, Oxford.

Ponomarenko, E., Anderson, D., Gregorich, E., 2018. A recommendation for a new descriptor for pyrogenic soil horizons in the Canadian Soil Classification System. In: Abstracts of North American Forest Soil Conference, International Symposium on Forest Soils, Quebec, Canada, pp. 87–88.

Ponomarenko, E., 2017. Методы изучения угольного спектра почв [Methods of the analysis of soil charcoal spectra]. In: Материалы III Всероссийской научной конфереӥии «Проблемы истории, методологии и сӧиологии почвоведения» KMK Scientific Press, Puschino, pp. 319–322.

Ponomarenko, E.V., Ponomarenko, D.S., Stashenkov, D.A., Kochkina, A.F., 2015. Podkhody k rekonstruktsii dinamiki zaseleniia territorii po pochvennym priznakam. [Approaches to reconstructing the patterns of human occupation from soil features and charcoal]. Povolzhskaya Archeologiya 1 (11), 126–160.

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

Ponomarenko, E.V., Crossland, D., Loo, J., 2013. Reconstructing tree species composition at the time of land clearance: two approaches compared. In: Damblon, F. (Ed.), Charcoal and Microcharcoal. Continental Records. Proceedings of the 4th International Meeting of Anthracology. BAR International Series 2486. Archaeopress, Oxford, pp. 195–202.

Ponomarenko, E.V., 1999. Metodicheskie podhody k analizu sukcessionnyh processov v pochvennom pokrove [The imprints of successions in the soil cover: methodology of the analysis]. In: Sukcessionnye Processy V Zapovednikah Rossii I Problemy Sohranenija Biologicheskogo Raznoobrazija [Forest Successions in Strict Natural Reserves of Russia and Preservation of the Biological Diversity]. SPb, pp. 34–57.

Ponomarenko, E.V., 1990. Pochvenno-morfologicheskie priznaki antropogennyh izmenenij lesnyh cenozov [Soil morphological features indicative of anthropogenic disturbances in forest ecosystems]. In: Populjacionnaja Organizacija Rastitel'nogo Pokrova Lesnyh Territorij (Na Primere Shirokolistvennyh Lesov Evropejskoj Chasti SSSR) [Population Ecology of the Forest Ecosystems (Case Study of the Broadleaved Forests of the European Part of the USSR)]. Puschino, pp. 66–81.

Porley, R.D., 2001. Bryophytes of arable fields: current state of knowledge and conservation. Bull Brit Bryol Soc 77, 50–62.

Poska, A., Väli, V., Kama, P., Tomson, P., Vassiljev, J., Kihno, K., 2017. The postglacial history of vegetation and land use dynamics in Karula upland [in Estonian]. In: In: Järvet, A. (Ed.), Yearbook of the Estonian Geographical Society, vol. 42. Vali Press OÜ, Tallinn, pp. 25–43.

Retallack, G.J., 1984. Trace fossils of burrowing beetles and bees in an oligocene paleosol, Badlands National Park, south Dakota. J. Paleontol. 58 (2), 571–592.

Salgado-Labouriau, M.L., Rull, V., 1986. A method of introducing exotic pollen for paleoecological analysis of sediments. Rev. Palaeobot. Palynol. 47 (1–2), 97–103.

Shaffer, E.L., 1966. Review of Information Related to the Charring Rate of Wood. US Forest Products Lab. Res. Note FPL-0145, Madison, Wisc Revised 1980.

Théry-Parisot, I., Chabal, L., Chrzavzez, J., 2010. Anthracology and taphonomy, from wood gathering to charcoal analysis. A review of the taphonomic processes modifying charcoal assemblages, in archaeological contexts. Palaeogeogr. Palaeoclimatol. Palaeoecol. 291 (1–2), 142–153.

Tolonen, M., 1978. Palaeoecology of annually laminated sediments in Lake Ahvenainen, S. Finland. I. Pollen and charcoal analyses and their relation to human impact. Ann. Bot. Fenn. 15, 177–208.

Tomson, P., Bunce, R.G.H., Sepp, K., 2015. The role of slash and burn cultivation in the formation of southern Estonian landscapes and implications for nature conservation. Landsc. Urban Plann. 137, 54–63.

Tomson, P., Bunce, R.G.H., Sepp, K., 2016. Historical development of forest patterns in former slash and burn sites in southern Estonia. In: In: Agnoletti, M., Emanueli, F. (Eds.), Biocultural Diversity in Europe. Environmental History, vol. 5. Springer, pp. 303–318.

Tomson, P., Kaart, T., 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. For. Ecol. Manag. 409, 845–862.

Vellak, K., Ingerpuu, N., Leis, M., Ehrlich, L., 2015. Annotated checklist of Estonian bryophytes. Folia Cryptogam. Est. 52, 109–127.

Vuorela, I., 1986. Palynological and historical evidence of slash and burn cultivation in Southern Finland. In: Behre, K.E. (Ed.), Anthropogenic Indicators in Pollen Diagrams. Balkema/ Rotterdam, Boston, pp. 42–53.

Walkley, A., Black, I.A., 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid in soil analysis. 1. Experimental. Soil Sci. 79, 459–465.

Whitehouse, N.J., 2000. Forest fires and insects: palaeoentomological research from a subfossil Burnt forest. Palaeogeogr. Palaeoclimatol. Palaeoecol. 164 (1–4), 231–246.