ARTICLE IN PRESS

Quaternary International xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Quaternary International

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

Anthracological and morphological analysis of soils for the reconstruction of the forest ecosystem history (Meshchera Lowlands, Russia)

Maxim V. Bobrovsky[a,*], Dmitry A. Kupriaynov[b], Larisa G. Khanina[c]

[a] Institute of Physicochemical and Biological Problems of Soil Science, Russian Academy of Sciences, Institutskaya, 2, Puschino, 142290, Russia
[b] M.V. Lomonosov Moscow State University, Faculty of Geography, Leninskie Gory 1, Moscow, 119991, Russia
[c] Institute of Mathematical Problems of Biology of RAS, Branch of the Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Vitkevicha 1, Pushchino, 142290, Russia

ARTICLE INFO

Keywords:
Charcoal
Tree uprooting
Soil morphology
Scots pine-dominated forests
Sandy soil
Fire history
Arable farming
Middle Russian Upland

ABSTRACT

Pedoanthracological methods have never been used for studying natural and anthropogenic factors of ecosystem dynamics in the area of the Middle Russian Upland. The article presents results of the first study of soil charcoal stratigraphy, taxonomy, and radiocarbon dating combined with morphological analysis of soil profiles performed for sandy soil (Podzols and Arenosols) in the Meshchera Lowlands. Charcoal samples from different soil patterns and horizons were taken from 19 soil pits in four forest sites. The taxonomic identification of charcoals was performed for 24 soil samples; 12 charcoal samples were radiocarbon-dated. The following three patterns of ancient pedoturbations were studied in the soil profiles: arable layers, root channels, and pits formed after treefalls with uprooting. Results of soil charcoal analysis were compared with pollen and microscopic charcoal analysis of the cores taken in the surrounding peats. *Pinus* charcoals of various age prevailed in all charcoal samples. Charcoal of *Betula* and *Sorbus* also occurred. The oldest charcoal fragments were 2610 cal. BP. The remaining charcoal samples were mainly grouped into three clusters: about 2200, about 900–1000, and later 500 cal. BP. We assume that most charcoal samples were associated with burning and subsequent plowing which provided the upper layer of the soil (arable layers and sometimes root channels) with charcoal fragments. Charcoals were most abundant in the deepest pits formed after ancient treefalls. Periods of accumulation of charcoals in the peatlands and in the soil did not coincide for the last several millennia in the study region: intensive mixing of charcoals into the soil began after a decrease in the flow of charcoals into the peats. We associate this with the changing dynamics of landscapes under the influence of anthropogenic factors.

1. Introduction

The convergence between the "classical" ecology and Quaternary paleoecology becomes an important feature of modern studies in paleoecology and historical ecology (Reitalu et al., 2014), together with use of complex methods to reconstruct the history of ecosystems and landscapes. Main methods of these studies usually include analysis of pollen data and dendrochronological analysis (Leopold and Völkel, 2007; Touflan et al., 2010; Adámek et al., 2015; Hultberg et al., 2015; Novák et al., 2018).

A number of studies have shown high importance of human activity for the dynamics of ecosystems and landscapes in the Holocene (Kirby and Watkins, 1998; Agnoletti and Anderson, 2000; Vera, 2000; Foster et al., 2003; Dearing et al., 2006; Reitalu et al., 2013; Smirnova et al., 2017).

At present, there are also novel methods which allow for reconstruction of changes in vegetation, soils and other components of ecosystems as well as for revealing of factors of these changes and for identification of the factors of ecosystem dynamics in the past. Pedoanthracology which studies wood charcoals from soils and sediments (Carcaillet and Thinon, 1996; Talon et al., 2005; de Lafontaine and Asselin, 2011; Nelle et al., 2013) can provide such modern methods of ecosystem reconstruction. Generally, pedoanthracology studies dynamics of wood species in space and time, and also history of fires, both of which can be applied to reconstruct history of human impacts associated with burning. An important feature of the pedoanthracological methods is the possibility to reconstruct discrete events in the history of local sites (Clark, 1988; Clark et al., 1998; Talon, 2010; Cunill et al., 2012; Robin et al., 2013; Robin and Nelle, 2014). However, except for studies of colluvial and aeolian deposits (Jansen et al., 2013; Larsen et al., 2016; Henkner et al., 2017), sampling of soil charcoals is not usually associated with functional analysis of charcoal location in the

* Corresponding author.
E-mail addresses: maxim.bobrovsky@gmail.com (M.V. Bobrovsky), dmitriykupriyanov1994@yandex.ru (D.A. Kupriaynov), khanina.larisa@gmail.com (L.G. Khanina).

https://doi.org/10.1016/j.quaint.2018.06.033
Received 6 March 2018; Received in revised form 15 June 2018; Accepted 21 June 2018

Please cite this article as: Bobrovsky, M.V., Quaternary International (2018), https://doi.org/10.1016/j.quaint.2018.06.033

soil profile, while many authors note an uneven distribution of charcoals along profiles (Carcaillet, 2001; Sass and Kloss, 2015; Kasin et al., 2016; Moser et al., 2017).

Charcoal movement in the soil is commonly associated with different types of soil regrouping determined by pedoturbation (Hole, 1961; Wood and Johnson, 1978). Tree uprootings appear to be a powerful natural factor of pedoturbation in forests (Schaetzl et al., 1989a; b; Šamonil et al., 2010). Soil charcoals associated with windfalls have already been studied, for example by Gavin (2003), Embleton-Hamann (2004), Talon et al. (2005), Šamonil et al. (2013), etc. Among anthropogenic factors of pedoturbation and charcoal translocation in the soil, various types of soil cultivation performed by different agricultural tools can be marked (Bobrovsky, 2010). Pedoturbations form various patterns in soil which can be revealed by soil morphological analysis. Therefore we assumed that morphological analysis of soil patterns could be applied to explain the origin of charcoals in the soil and causes of their concrete locations. The main hypothesis of our research was that uneven distribution of charcoals in the soil is associated with pedoturbations: charcoal position within the soil ares controlled by a type of pedoturbation responsible for the charcoal movement.

The aim of our research was to perform a functional analysis of charcoal location in the soil: to study soil charcoal stratigraphy and taxonomy, to perform radiocarbon dating of soil charcoals, and to associate their results with morphological analysis of soil pits. It is simpler to study traces of pedoturbations in sandy soils: due to the large size of the particles, leaching is difficult there and pedoturbations become the main factor of soil mixing and of particles regrouping. Therefore, we selected *Pinus sylvestris* forests on sandy soils in the Meshchera Lowlands as the object of our investigation. The general purpose of our research was to study the history of ecosystems in the Meshchera Lowlands and to assess natural and anthropogenic factors of ecosystem dynamics in the Holocene, that would be compliment earlier paleoecological reconstructions executed on samples from surrounding peats (Dyakonov and Abramova, 1998; Abramova, 1999; Novenko et al., 2016). Therefore we also compared results of soil charcoal analysis with pollen and microscopic charcoal analysis of the cores taken in surrounding peats (Novenko et al., 2016).

2. Study area

Study area was located in the southeastern part of the Meshchera Lowlands: in the Klepikovsky district of the Ryazan region; about 160 km south-east from Moscow and about 70 km north-east from Ryazan (Fig. 1). The area is a part of Polesie landscape represented by sandy lowlands and located on a border of the nemoral and hemiboreal forest region (Smirnova et al., 2017). *Pinus sylvestris* (Scots pine) forests, which dominate on sandy soils in Polesie, are refugees of boreal vegetation, a geographically separated analogue of boreal coniferous forests of northern Europe in more southerly areas (Novák et al., 2012). The role of fires in the dynamics of vegetation and soils is comparable to that observed in boreal forests (Smirnova et al., 2017).

The study area is located in the Pra River basin. Undulating, moraine-fluvio-glacial plains formed by the Middle Pleistocene (MIS 6) deposits of varying thickness and drainage condition prevail in the area (Novenko et al., 2016). The highest elevations in the relief are occupied by eolian-fluvio-glacial hilly plains and small ridges. Numerous bogs are located in small depressions formed by thermokarst processes during the Last Glacial Maximum (Ivanov, 1995). The thickness of the Quaternary deposits is about 20 m (Annenskaya et al., 1983; Velichko et al., 2001). There are numerous lakes in the area, called Lakes Klepikovskie, including Lake Velikoye and Lake Beloye. The water's edge is located at elevation from 111 to 112 m above sea level.

The climate in the area is temperate continental. In 1995–2015, average annual temperature was 3.8 °C; average temperature of July and January was 18.6 °C and minus 11.2 °C, respectively; average annual precipitation was 550 mm (www.ecad.eu; Tuma weather station). The high coefficient of humidity (1.2–1.4) and the flat topography of the area lead to fast paludification.

Sandy soils Podzols and Arenosols prevail in the region; Stagnic Podzols and Histosols are common in depressions on the border with peats. Soils taxons are given in accordance with World reference base for soil resources (IUSS Working Group, 2015).

3. Materials and methods

3.1. Location and vegetation of the sites

Soil and soil charcoal samples were collected in four sites in June 2017 (Fig. 1). Site 1 was located close to Pridorozhnoe peatland (55.21055 N, 40.24376 E); Site 2 was located close to Chernoe-1 peatland (55.29844 N, 40.23931 E); Site 3 was located close to Studencheskoe peatland (55.26686 N, 40.20630 E), and Site 4 was located close to a peatland without name situated near Lake Beloe (55.27364 N, 40.23502 E).

All sites contained small ridges and depressions with shallow swamps. There was neither deadwood, nor pits or mounds formed after treefalls with uprooting in the sites. *Pinus sylvestris* forest with green mosses in the ground layer occupied gentle ridges. According to the tree cores, Scots pines were from 50 to 70 years old; pines had probably been planted, as we could assume from their regular spatial structure. *Betula pendula* also often occurred in the overstorey. *Quercus robur* and *Picea abies* were found in the sparse undergrowth. Except for *Quercus robur*, other broad-leaved trees, such as lime (*Tilia cordata*), maple (*Acer platanoides*), ash (*Fraxinus excelsior*), and elm (*Ulmus glabra*) rarely occur in Polesie, and they were absent in the study sites though general areas of distribution of these species cover the Polesie region (Smirnova et al., 2017). In the understorey, *Sorbus aucuparia* and *Frangula alnus* were found. *Luzula pilosa*, sometimes *Vaccinium vitis-idaea, Pteridium aquilinum* and *Festuca* sp. dominated in the poor field layer, which covered 5–15%; green mosses covered 25–95% of the bottom layer (the values were visually estimated). Shallow swamps in depressions were covered by separately growing *Pinus sylvestris* and *Betula* spp. individuals; cotton-grass (*Eriophorum vaginatum*) and *Ericaceae* (*Ledum palustre, Chamaedaphne calyculata,* and *Oxycoccus macrocarpus*) occur in the field layer; there was a dense cover of sphagnum in the bottom layer.

3.2. Morphological description of soil profiles

We reconstructed ecosystem history based on morphological analysis of patterns in soil profiles. It was possible, because various past events in the ecosystem affected the soil and led to changes in soil morphological structure: they changed the soil material or caused the soil translocation. Specific patterns thus appear in the soil and they can be distinguished in the profile. In the study region, main impacts leading to pedoturbations are as follows: growth and death of trees that create root channels in the soil; pits after treefalls with uprooting; and soil cultivation with agricultural tools, primarily arable tools. The most complete technique for diagnostics of various impacts on ecosystem by soil morphological analysis was proposed by Ponomarenko (1999); it was also specified by Bobrovsky (2010) and it is briefly described below.

Windthrows, creation of pit-and-mound topography and movement of soil material due to treefalls with uprooting are described fairly well (Armson and Fessenden, 1973; Allen, 1992; Beatty and Stone, 1986; Schaetzl et al., 1990; Šamonil et al., 2010, 2016; Pawlik et al., 2017; Phillips et al., 2017; Valtera and Schaetzl, 2017). Soil charcoals associated with windfalls have also been studied, for example by Gavin (2003), Embleton-Hamann (2004), Talon et al. (2005), Šamonil et al. (2013). With time, when pits and mounds disappear from the soil surface, some traces of soil translocation remain in the soil in a form of specific morphological patterns (Ponomarenko, 1999; Šamonil et al.,

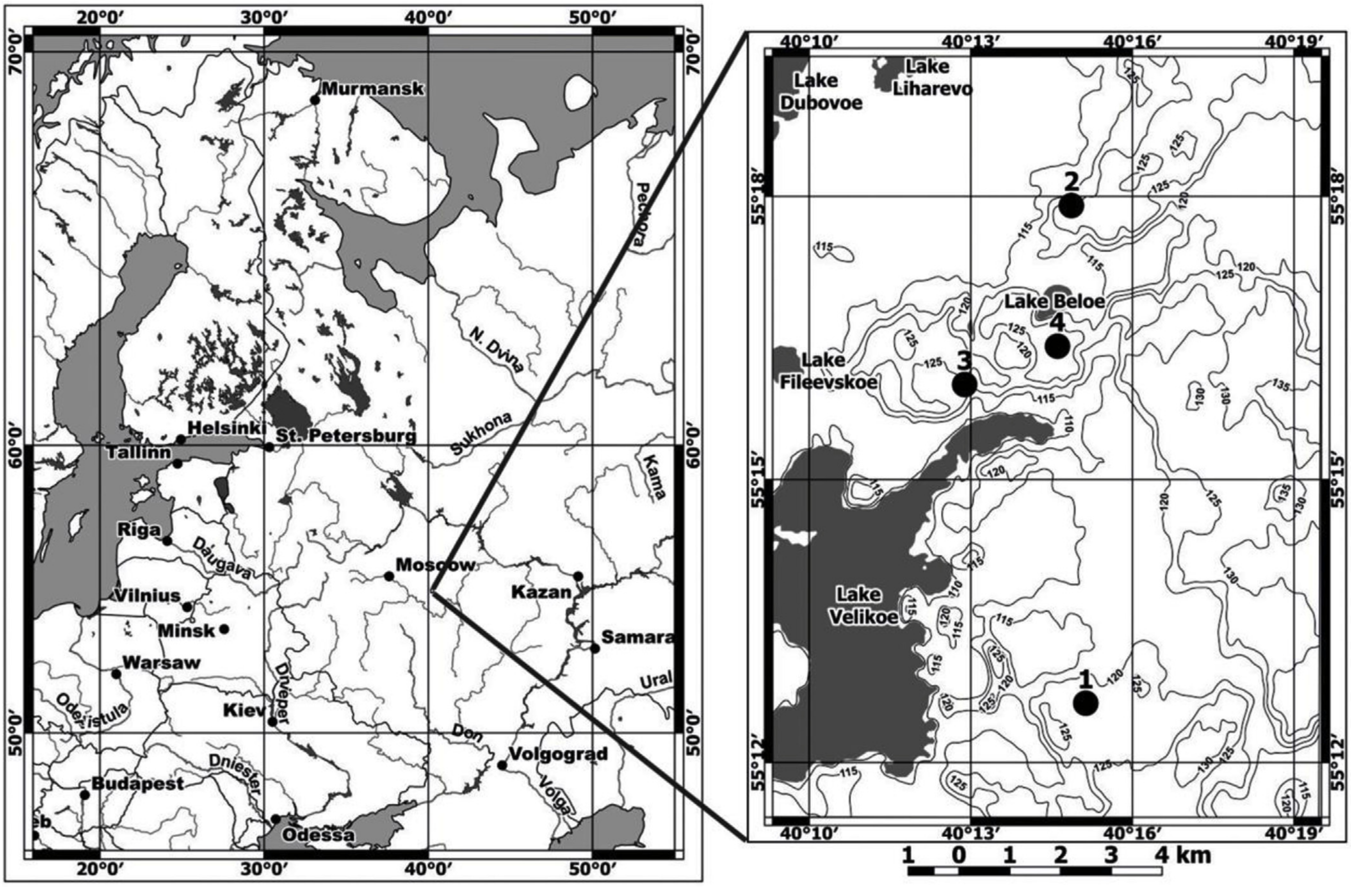

Fig. 1. Location of the study area and sites from 1 to 4.

2013; Bobrovsky and Loyko, 2016). These patterns include: (1) treefall pits (cauldrons), (2) spotted or streaky structures from the material of different contrast, including single lumps/spots, (3) blocks of "buried material", (4) bleached soil material, (5) signs of hydrogenous changes of soil material (gleization), and (6) soil inclusions (litter and charcoal). Among treefall-related pedoturbations, the first two patterns occur most often (Bobrovsky and Loyko, 2016).

Another pattern, root channels which have been formed by roots of live trees, also often occurred in soil profiles (Bobrovsky, 2010; Pawlik et al., 2016). If trees die and do not fall with uprooting, or if trees were cut, their roots remain in the soil and gradually decompose there. Root channels can be filled by decomposing root matter or by the soil. Sharp root channels in soil profiles are formed after such trees as birch, aspen, and pine, which have a denser bark of the roots than their inner part (Ponomarenko, 1999). The root bark of these trees decomposes more slowly than the root inner part and forms "a container" which is filled with soil material from the upper soil layers as the wood decomposes. Root channels have a circular section in the horizontal plane, which is different from frost wedges, which have an extended structure in the horizontal plane. It is also possible to distinguish in the soil profile between the cases when roots decomposed inside the soil and when they were pulled out artificially from the soil. To get out a tree stump after felling, a man had to cut roots at the soil surface and then to rock and pull the stump with the root system. If this was the case, the filling of the root channels occurred quickly, almost simultaneously, with large clumps. Due to the rocking and pulling of the stump, the upper part of the root channel becomes enhanced with indistinct edge. Thus a partial destruction of the upper edge of a root channel and the filling of the channel with large clumps of mineral soil are signs of artificial uprooting of tree stumps after felling.

The main sign of agricultural cultivation of soil is an arable horizon (a specific upper layer of the soil) which often occurs with a distinct bottom line ("plow sole") in the profile (see, for example, Moser et al., 2017). Peculiarities of the arable horizon structure depend on a type of the applied soil cultivation tool (harrow, ard, plow, or wooden plow). However it is difficult to distinguish patterns which were formed by different tools after repeated impacts within approximately the same soil thickness. Features of the arable horizon structure are mostly determined by the system of agriculture (slash-and-burn, or shifting, or three-field system) including presence and frequency of fertilization, depth of soil cultivation, etc. Some of these features can be identified by morphological analysis of the soil profile.

For the each site, one soil profile with a depth of about 150 cm and several shallow pits with a depth of about 50 cm were dug and described. All soil pits were located randomly within the sites, but mainly on tops of slopes. The latter was done in order to more accurately determine the original location of charcoal pieces, as they have a good ability to move over long distances, primarily with water (Carcaillet et al., 2007). As a result of the top location of dug pits, the distances of the possible transfer of charcoals would be no more than the first 10 m. Only two pits (9 and 12) were dug in the lower part of the slopes and charcoals had been able to transport from the adjoin slopes from a greater distance, but no more than 100 m.

Charcoal was taken from localities in the pits where charcoal fragments were visually distinct. Totally 19 soil pits were sampled for pedoanthracological analysis and all pits were described: sketches and photographs were made, location of charcoals and location of patterns associated with ancient plowing, treefall with uprooting and channels of tree roots were registered. Live roots and traces of small roots were not registered.

3.3. Charcoal sampling and analysis

Anthracological samples of 1000 cm^3 were randomly taken from each soil pattern and horizon. Samples were dried on air and gently sieved wet through 2 mm mesh size (Carcaillet and Talon, 1996). Charcoal fragments were extracted by hand from the sieved samples and then weighed to calculate charcoal concentration (or anthracomass, g of charcoal per kg of dry soil).

Taxonomic identification of charcoals was performed using a reflected light microscope (40-400x) using wood anatomy atlas (Benkova and Schweingruber, 2004). The transverse, radial and tangential anatomic planes of each charcoal were observed to identify charcoals at the genus taxonomic level.

Twelve largest charcoal specimens from 10 soil pits were radiocarbon-dated in the Institute of geochemistry and geophysics of the National Academy of Sciences of Belarus (IGSB). Radiocarbon age of the charcoal was determined by the liquid scintillation counting (LSC). Standard techniques including acid-base-acid (ABA) treatment were performed. The samples were placed in 1M HCl and heated to 80 °C for 1 h, centrifuged and decanted. Then the samples were washed with 0.1 M NaOH and treated with dilute HCl, then washed with deionized water and dried at 105 °C. The activity of ^{14}C was determined in benzene using a Quantulus 1220 liquid scintillation counter.

The ^{14}C dates were calibrated using the program Calib 13.0 and the calibration dataset Intcal13 (Reimer et al., 2013). Calculations were done at 2σ level.

4. Results

4.1. Soil types and soil horizons

Podzols and Arenosols prevailed in the study areas (Table 1). Various patterns of ancient pedoturbations (Fig. 2, Table 2) were described in the profiles including arable layers (al), pits of ancient treefalls (t-pit), and root channels (rc). Besides traces of concrete ancient pedoturbations, a layer with their traces, usually in the form of spotted or streaky structures, and sometimes in the form of root channels, was also distinguishable in the profiles. A bottom line of this turbated layer was indicated as tl (Fig. 2).

Profile 1 was located in Site 1. Soil was Umbric Brunic Arenosol (Nechic) with horizons O – A – Bw – C. There was an ancient arable layer (al1), a lower part of which included traces of various turbations; we distinguished this lower part as a separate arable layer (al2). Deeper, there were no clear patterns of pedoturbations, but the horizon Bw included a non-contrast spotted material with a border in form of large cauldrons.

Profile 8 was located in Site 2. Soil was Entic Podzol (Lamellic) with horizons O – A – Bhs and Bs (E) – BC. Two arable layers (al1 and al2), many root channels (from rc1 to rc9) and several patterns of ancient pits were distinguished there. A patchy mixed layer with lamellaes (tl) and a coarse-wavy bottom line were located deeper.

Profile 10 was located in Site 3. Soils were Entic Podzol (Lamellic) and Albic Brunic Arenosol (Lamellic) with horizons O – A (E) – Bhs, Bs, E − Bs and Bts – BC. There were an ancient arable layer (al) and a deeper located pattern of a tree-uprooting ancient pit (t-pit). There were also two root channels (rc1 and rc2) superimposed on a heterogeneous mixed layer (tl).

Profile 13 was located in Site 4. Soil was Someriumbric Stagnic Albic Podzol with horizons O – A – Bhs – Bs and Bts – BC. There were an ancient arable layer (al) and a spotted layer from mixed E and Bhs (tl1) under the arable layer. Many ancient root channels (from rc1 to rc13) adjoined tl1. A mixed layer of diverse material (tl2) was located deeper. It was possible to assume a boundary of an ancient tree-uprooting pit (t-pit) in this mixed layer.

Table 1
Soil types and locations of soil pits in the Meshchera Lowlands.

Site	Pit	Relief	Soil
1	1	flat top of the ridge	Umbric Brunic Arenosol (Nechic)
1	2	slope	Umbric Brunic Arenosol (Nechic)
1	3	slope	Umbric Brunic Arenosol (Nechic)
1	4	slope	Umbric Brunic Arenosol (Nechic)
1	5	slope	Umbric Brunic Arenosol (Nechic)
1	6	slope	Umbric Brunic Arenosol (Nechic)
1	7	slope	Umbric Brunic Arenosol (Nechic)
2	8	flat top of the ridge	Entic Podzol (Lamellic)
2	9	bottom of the slope	Stagnic Albic Podzol
3	10	flat top of the ridge	Entic Podzol (Lamellic)
3	11	flat top of the ridge	Entic Podzol (Lamellic)
3	12	bottom of the slope	Stagnic Folic Albic Podzol
4	13	flat top of the ridge	Someriumbric Stagnic Albic Podzol
4	14	flat top of the ridge	Someriumbric Stagnic Albic Podzol
4	15	flat top of the ridge	Someriumbric Stagnic Albic Podzol
4	16	flat top of the ridge	Someriumbric Stagnic Albic Podzol
4	17	flat top of the ridge	Someriumbric Stagnic Albic Podzol
4	18	flat top of the ridge	Someriumbric Stagnic Albic Podzol
4	19	flat top of the ridge	Someriumbric Stagnic Albic Podzol

4.2. Soil charcoals stratigraphy

Twenty four charcoal samples were taken from 19 soil pits (Table 3). Charcoals were found at a depth of 4–45 cm. In most cases (11 samples) the charcoals were found in old arable horizons, where they occurred unevenly by light clusters; in Profile 1, the charcoals were also located as narrow layers in the lower part of the arable horizon (samples 1-1 and 1–2, Fig. 3a). Three charcoal samples were taken from sediments in the bottom part of the slopes (pits 9 and 12). Two samples were located in ancient root channels (Fig. 3f). Five samples were found in the pits of ancient treefalls (Fig. 3i). For three samples in Site 4, it was not possible to link the charcoal positions to patterns of ancient pedoturbations in the profiles.

4.3. Soil charcoal taxonomy and concentration

From 4 to 100 fragments of the charcoal occurred in the samples. Totally 237 charcoal fragments (4.59 g) were taxonomically identified. Trees of three genera were identified: *Pinus*, *Betula* and *Sorbus* (Table 3). The *Pinus* charcoals were absolutely predominant: they occurred in all samples from all sites, whereas *Sorbus* charcoals occurred once in Site 3 and *Betula* charcoals were twice attested in Site 1 and 3. Charcoal concentration varied from 1.54 to 133.36 g/kg of dry soil (Table 3). There was no clear correlation between the depth of charcoal location and their anthracomass (Fig. 4), but four samples with the largest charcoal concentration were taken from a depth of 15 cm and more, two of them were taken from the pits of the ancient treefalls (samples 3–5 and 4–2).

The mean charcoal concentration in Sites 1, 2, 3 and 4 was 8.1 ± 5.8, 10.8 ± 1.8, 24.1 ± 6.5 and 25.8 ± 30.7 g/kg of dry soil, respectively. For sites 3 and 4, a great proportion of the charcoal concentration was provided by samples 3–5 and 4–2 which were taken from ancient pits of treefalls.

4.4. Radiocarbon dating of soil charcoal samples

The radiocarbon dating of 12 charcoal samples showed that the charcoal age varied from 55 ± 80 to 2670 ± 125 cal. BP (Table 4). The ranges (2δ) of radiocarbon dates formed three clusters (Fig. 5): about 2200 cal. BP (the Early Iron Age), about 900–1000 cal. BP (the Early Middle Ages) and the latest 500 cal. BP (the Modern Period). Only for three samples (IGSB-1781, 1776 and 1779) probability peaks were located between these clusters. There was a large gap in time between three samples dated to the Early Iron Age and the remaining twelve samples dated to the Middle Ages and the Modern Period.

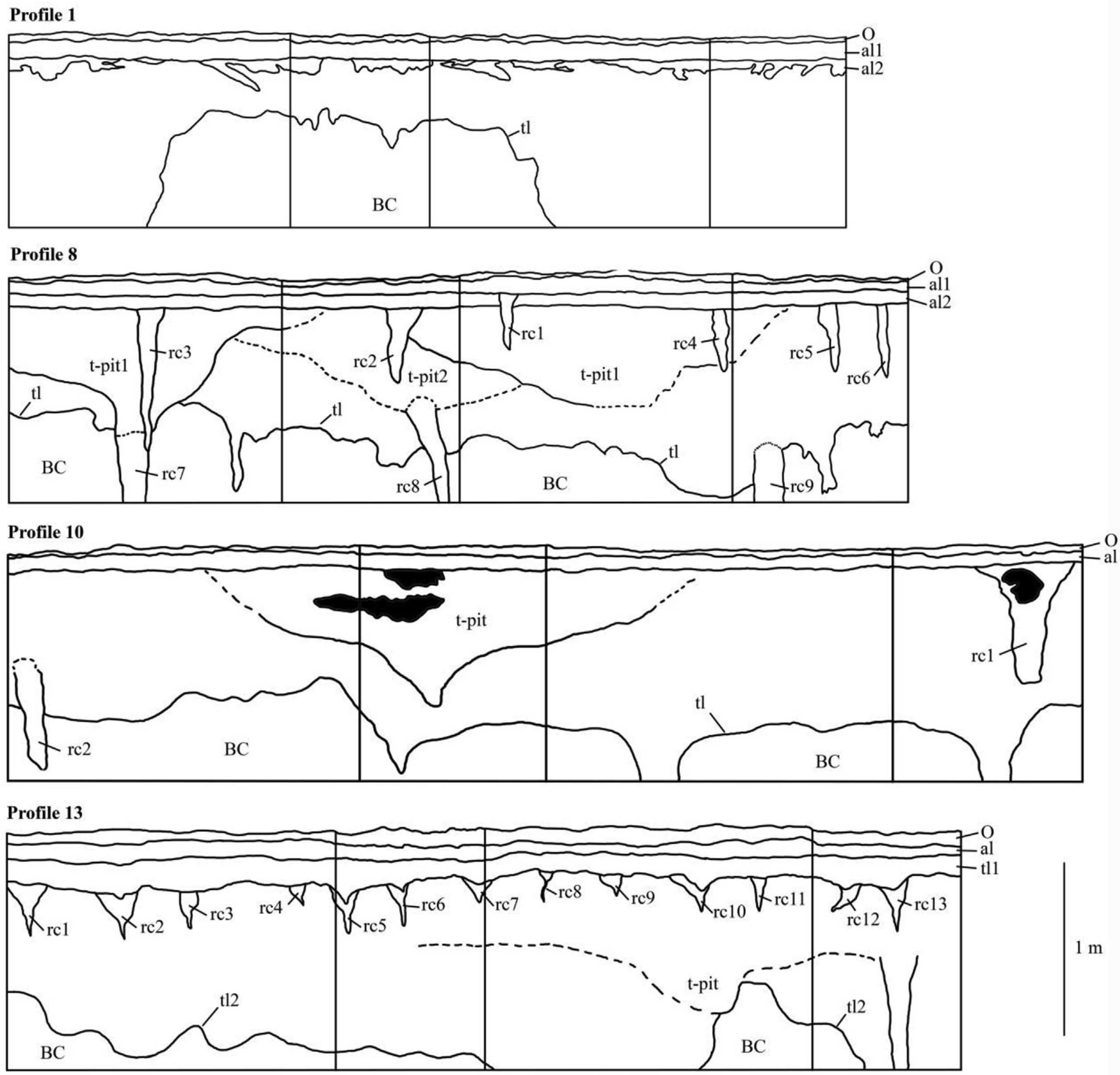

Fig. 2. Patterns of ancient pedoturbations in soils of the Meshchera Lowlands: al –arable layer, rc – root channel, t-pit – pit of treefall, tl – bottom line of the layer with visually distinguishable signs of soil mixing. Large accumulations of charcoals are blackened. See description in Table 2.

In general, there was a positive correlation between the age of charcoals and the depth of their location in the pits (Fig. 6). A notable exception was shown in sample 4–1 from horizon A (old arable layer) in Site 4. A weak positive correlation was visible between the anthracomass of the samples and their age (Fig. 7). Two samples (3–5 and 4–2) mentioned above and taken from pits formed after treefalls had the largest anthracomass and the maximum age.

4.5. Soil charcoals and soil patterns

4.5.1. Site 1, profile 1

The arable horizon comprised two layers. The upper layer (al1) was relatively homogeneous with a very even bottom line, and haven together, this indicated that the soil had been repeatedly plowed up. The depth of the ancient tilth (14 cm) was common for arable tools, such as an ard or a wooden plow (“sokha” in Russian) (Fig. 2, Table 2). Charcoal pieces were disseminated through the layer. Two dates were identified from soil pits 4 and 6 located near the soil profile on a slope at the same soil layer as al1. These dates were 140 ± 105 and 280 ± 125 cal. BP; it suggests the existence of shifting cultivation or slash-and-burn at that time in the site. These agriculture systems included consecutive stages of forest burning, plowing, free forest development and forest burning again. Charcoal pieces were partially plowed into the arable horizon; most likely they originated from the burning for agriculture. However, we cannot exclude a version that these charcoal pieces had been formed by accidental fires, and then they were plowed into the soil. There were no clear traces of root systems of trees that grew between periods of plowing.

Table 2
Patterns in the study soil profiles in the Meshchera Lowlands.

Label	Pattern/horizon	Description	Depth, cm
Site 1, Profile 1			
O	litter	moderately decomposed litter of *Pinus sylvestris* prevails	0–4
al1	arable layer, depth 14 cm, an even bottom line	relatively homogeneous horizon A, reddish gray (5Y 5/2), spots of Bw, brown (7.5 YR 5/4), *albic*, pinkish gray (7.5 YR 7/2); sparse charcoals < 0.5 cm	4-18 (16)
al2	lower part of arable layer; uneven bottom line; patches as traces of impacts of an arable tool (an ard) are visible	spots of An umbric (rarely *albic*) in Bw, strong brown (7.5 YR 5/6); sparse charcoals < 0.5 cm, 0.5–2 cm (sample IGSB-1773), small layers of charcoals in some places	18-24 (30)
tl	bioturbated horizon, bottom line in a form of large pits	Bw, reddish yellow (7.5 YR 6/6), spotted	24-50 (> 120)
C		pinkish gray (7.5 YR 7/2)	> 50 (120)
Site 2, Profile 8			
O	litter	moderately decomposed litter of *Pinus sylvestris* prevails	0–3
al1	arable layer, depth 11 cm, even bottom line	relatively homogeneous, well-mixed A, brown (7.5 YR 5/2)	3–14
al2	arable layer, depth 17 cm, even bottom line	heterogeneous, slightly mixed A, Bs and Bhs, yellowish brown (10 YR 5/4) prevails	14–20
rc1	filled root channel, partial destruction of edges, diameter 7 cm	filled by large spots: in the upper part spots of Bhs reddish gray (5 YR 5/2), in the lower part Bs, brown (7.5 YR 4/4)	14–50
rc2	filled root channel, destruction of edges, diameter about 13 cm	filled by large spots: in the upper part spots of Bhs reddish gray (5 YR 5/2), in the lower part Bs, brown (7.5 YR 4/4), charcoals 0.5–2 cm (sample IGSB-1774) at depth 25–30 cм	20–65
rc3	filled root channel, partial destruction of edges, diameter about 8 cm	filled by spots, relatively homogeneous (well mixed) material, mainly Bs brown (7.5 YR 5/4)	20–85
rc4	filled root channel, diameter 7 cm	ferruginous root pseudomorph, dense, black (5 YR 2.5/1)	20–55
rc5	filled root channel, partial destruction of edges, diameter 5 cm	filled by relatively homogeneous material: in the upper part Bhs, reddish gray (5 YR 5/2), in the lower part E, pinkish gray (7.5 YR 7/2)	20–50
rc6	filled root channel, partial destruction of edges, diameter 5 cm	filled by spotted material in the upper part, mainly Bs strong brawn (7.5 YR 4/6), in the lower part E pinkish gray (7.5 YR 7/2)	20–55
rc7	filled root channel, diameter about 12 cm	filled by Bhs, light yellowish brown (10 YR 6/4) and E, very pale brown (10 YR 8/2)	80- > 125
rc8	filled root channel, diameter about 14 cm	filled by E, very pale brown (10 YR 8/2)	95- > 125
rc9	filled root channel, destruction of edges, diameter about 12 cm	pinkish white (7.5 YR 8/2)	80–120
t-pit1	two patterns of a treefall pit of rotational treefall on three walls, depth > 82 cm	filled by large parts of various material: in front part Bhs prevails, dark reddish gray (5 YR 4/2), in rest parts Bs, brown (7.5 YR 5/4)	20–82
t-pit2	treefall pit pattern, depth > 80 cm	filled by no contrast Bs, pinkish gray (7.5 YR 7/2)	20–80
tl	lower part of bioturbated (mixed) layer, bottom line is large-wavy, sometimes as tongues	Bs, spotted with lamellaes, main colour is pinkish white (7.5 YR 8/2)	< 115
BC		pinkish white (5 YR 8/2)	> 115
Site 3, Profile 10			
O	litter	moderately and highly decomposed litter of *Pinus sylvestris* prevails	0-5 (7)
al	arable layer, depth 10 cm, even bottom line	locally relatively homogeneous (well mixed) material, whereas it differs in different sections of the profile; A prevails, pinkish gray (7.5 YR 6/2), spots of E in the upper part, pinkish white (7.5 YR 8/2); Bhs prevails on the wall 3a, pinkish gray (5 YR 6/2); sparse clusters of charcoals < 0.5 cm, 0.5–2 cm (sample IGSB-1777).	5–15
t-pit	treefall pit pattern, depth > 70 cm	large parts of various material including E white (5 YR 8/1), Bs, light brawn (7.5 YR 6/4) and very pale brown (10 YR 8/4), Bhs yellowish red (5 YR 4/6); fine-grained structure, charcoals > 2 cm (sample IGSB-1778) on the wall 3b in the form of two large clusters	15–70
rc1	filled root channel, partial destruction of edges, diameter about 18 cm	filled by spotted material, mainly E white (5 YR 8/1) with Bs, pinkish gray (5 YR 7/2), depper Bs greyish brown (7.5 YR 6/2) which are colored by charcoal in the upper part, charcoals 0.5–2, > 2 cm (sample IGSB-1776)	15–85
rc2	filled root channel, diameter 9 cm	filled by spotted material, mainly Bts, pinkish gray (7.5 YR 7/2)	65–140
tl	bioturbated (mixed) layer in the lower part, bottom line is large-wavy; several root channels going deep, diameter about 12 cm	various material of horizons Bs and Bts, mainly very pale brown (10 YR 8/4, 8/2); many spots inside probable pits with unclear lateral boundaries up to a depth of 90–100 cm; material in the relatively large root channels (mainly Bts) is deeper 100 cm	< 100
BC		pink (7.5 YR 7/4), pinkish gray (7.5 YR 7/2)	> 100 (140)
Site 4, Profile 13			
O	litter	moderately decomposed litter of *Pinus sylvestris* prevails	0–10
al	arable layer, depth 6 cm, uneven bottom line	relatively homogeneous (well mixed) material, A, dark reddish brown (5 YR 3/2), sparse charcoals < 0.5 cm, 0.5–2 cm (sample IGSB-1780)	10–16
tl1	turbated, strongly mixed layer with a wavy bottom line	spotted, *albic* E prevails, pinkish gray (5 YR 7/2), spots of AE, reddish gray (5 YR 5/2), Bhs weak red (2.5 5/2), locally Bs, brown (7.5 YR 4/4)	16-26 (35)
rc1-rc13	root channel, destruction of edges in the upper part	filled by tl1 in the upper part, ferruginous root pseudomorph, in the lower part, dense, dark reddish brown (7.5 YR 2/2), with boundaries of varying degrees of clarity	26-50 (43–57)
t-pit	treefall pit pattern, depth > 95 cm	filled by relatively un-contrast material, Bs in the upper part, strong brown (7.5 YR 4/6) and brown (7.5 YR 5/4)	26–95
tl2	lower part is bioturbated (mixed) layer, wavy border	various material of horizons Bs and Bts, spots inside probable pits with unclear lateral borders	< 125
BC		pinkish gray (7.5 YR 7/2)	> 125

The lower layer of the arable horizon (al2) was the result of an earlier and slightly deeper plowing. This layer was quite heterogeneous: probably the material of the upper horizon was buried in the horizon Bw by an arable tool. This layer was noticeably darker than the upper layer; charcoal pieces were abundant.

In some places the charcoals had been so plowed in the soil that we could see small layers parallel to the soil surface without any other material in the horizon Bw (Fig. 3a). This suggests that forest at this site was burned and the soil was plowed soon, probably by an ard, with the charcoal being scattered into the furrows and then buried. Charcoals

Table 3
Results of charcoal analysis from the Meshchera Lowlands.; patterns: al – arable layer, rc – root channel, t-pit – pit of treefall, sed – slope sediment. Analysis: D. Kupriyanov.

Site	Pit	Sample	Horizon	Pattern	Depth, cm	No. taxa charcoal			No. taxa/ samples	No. defined charcoals	No. charcoals per 1000 cm^3	Charcoal concentration, $g^* kg^{-1}$
						Pinus	*Betula*	*Sorbus*				
1	1	1–1	A, Bs	al	20	12			1	12	30+	25.98
1	2	1–2	A, Bs	al	20	6			1	6	10+	1.54
1	3	1–3	A	al	4–10	5			1	4	4+	2.39
1	4	1–4	A	al	4–10	5			1	5	10+	9.29
1	5	1–5	A	al	4–8	7			1	7	10+	3.00
1	6	1–6	A	al	4–8	7			1	7	10+	9.29
1	7	1–7	A	al	4–10	9	2		2	12	30+	4.95
2	8	2–1	Bhs	rc	25–30	5			1	5	10+	8.96
2	9	2–2	A	sed	10–15	11			1	11	30+	12.60
3	10	3–1	A	al	4–24	14			1	14	100+	30.92
3	10	3–2	Bs + E	rc	20–35	13			1	13	50+	15.91
3	10	3–3	Bhs, E	t-pit	35–45	13			1	13	50+	19.51
3	10	3–4	Bhs, Bs	t-pit	35–45	13			1	13	100+	22.39
3	10	3–5	Bs	t-pit	35–45	11			1	11	50+	83.35
3	11	3–6	A	al	4–15	13			1	13	100+	7.45
3	12	3–7	Egh	sed	7–9	4	1		2	5	10+	0.43
3	12	3–8	Egh	sed	14–17	8		4	2	12	15+	12.71
4	13	4–1	A	al	4–15	7			1	7	10+	12.23
4	14	4–2	Bs	t-pit	20–25	14			1	14	50+	133.36
4	15	4–3	A	al	4–8	10			1	10	50+	9.93
4	16	4–4	Bhs		15–20	7			1	7	10+	3.0
4	17	4–5	Bs		10–15	9			1	9	20+	2.51
4	18	4–6	Bs		20–25	15			1	15	44	2.82
4	19	4–7	Bs	t-pit	30–40	12			1	12	40+	16.85

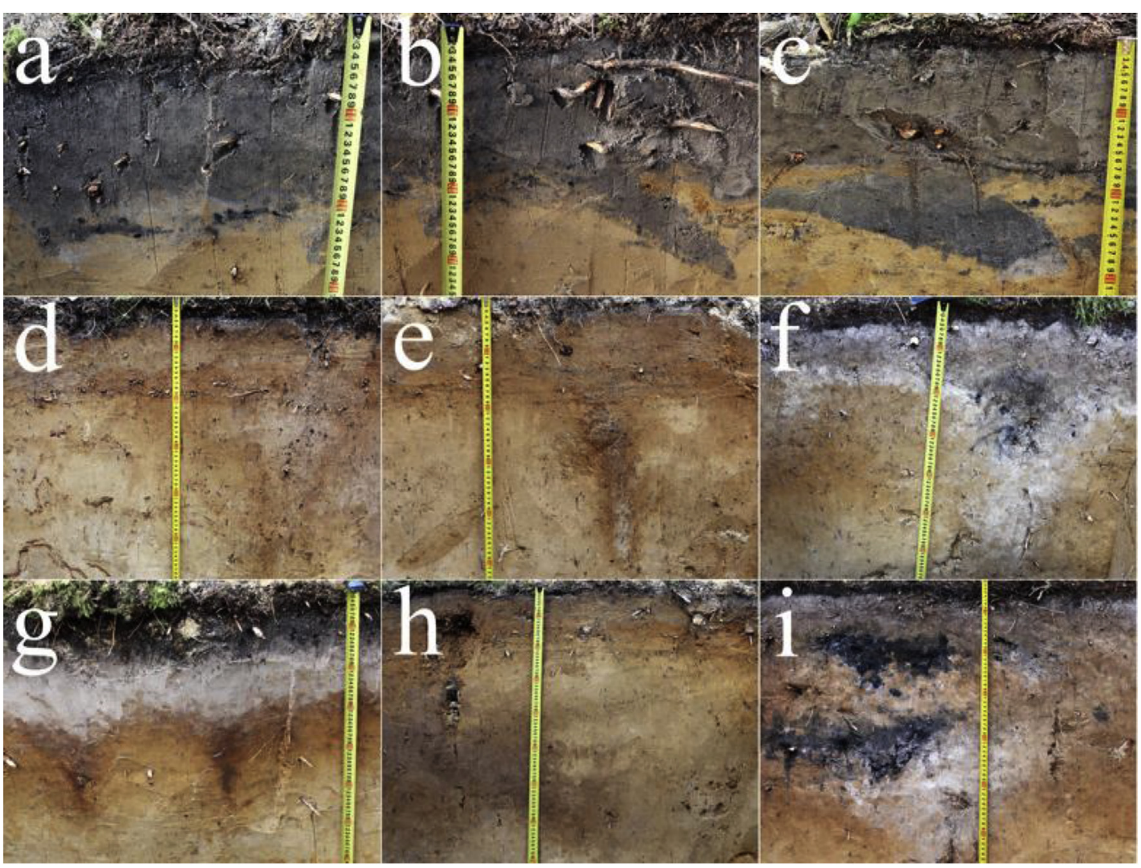

Fig. 3. Details of selected profiles with different patterns: an arable layer with a charcoal layer in the bottom (Profile 1); b, c traces of arable tools (Profile 1); d–g filled root channels: d rc2 and e rc5 in Profile 8, f rc1 in Profile 10, g rc2 and rc3 in Profile 13; h pit of ancient tree-uprooting (t-pit1, Profile 8), i pit of ancient tree-uprooting with charcoal layers (t-pit, Profile 10).

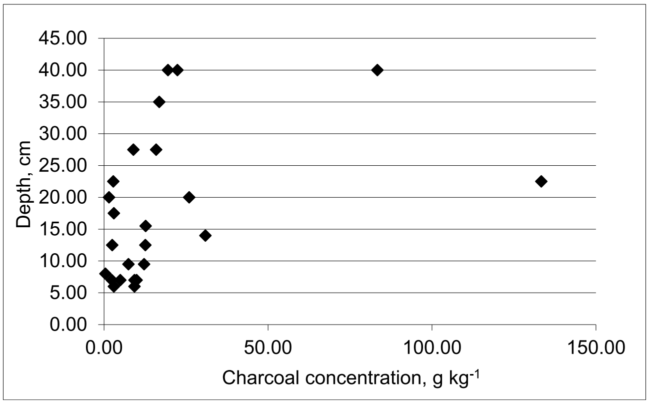

Fig. 4. Charcoal concentration and depth of charcoal sampling.

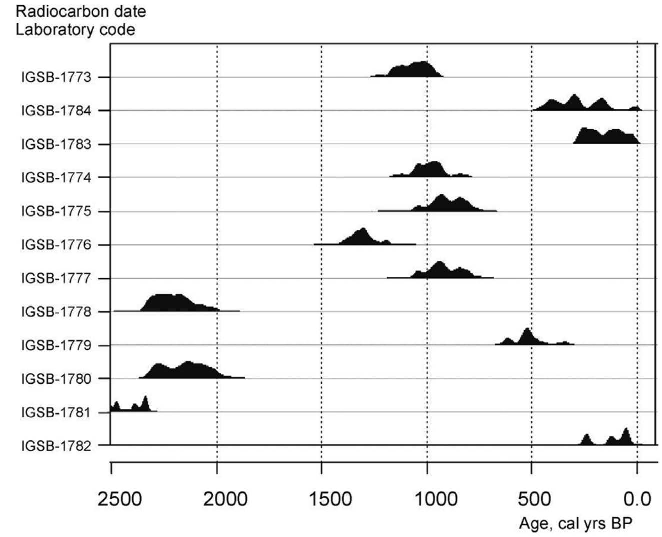

Fig. 5. Probability curves of calibrated radiocarbon dates for charcoals from the Meshchera Lowlands.

from this layer were 1075 ± 75 cal. BP. In two places of this arable layer, there were specific structures (Fig. 2, Profile 1 and Fig. 3b and c), which could be traces of the use of an ard which entered the soil deeper than necessary, or stuck, and then was pulled backward. As a result, a cavity in the form of an ard was formed in the soil; this cavity was then filled with a material of the upper level. The uneven boundary of the layer and the "stuck-up" of the ard in sandy soil could be caused by small weight of the arable tool and a weak tractive force and/or by the presence of obstacles in the soil such as tree roots.

The middle horizon Bw was the least contrast in this profile among all the other profiles. There were no clear patterns formed by treefalls with uprooting and root channels, although some spots were present up to a depth of 50–120 cm, the spots probably originated from the ancient treefalls with uprooting. One possible reason for the lack of more contrast material in the profile was the truncation of the upper part of the profile as a result of erosion, because the profile was located at the top of a small hill.

4.5.2. Site 2, profile 8

The profile 8 had the most mosaic structure among the all four full-sized soil profiles. Two arable horizons were well distinguishable. The upper layer was homogeneous with a rather even bottom line. As it was already commented for Site 1, this indicated repeated plowing in the past. In the second arable horizon, the material was poorly mixed; contrasting spots occurred; that indicated a single or few plowing in the past. The soil was treated to a relatively great depth (17 cm); an even bottom line was also formed. This result could be obtained if a relatively large arable tool was used to plow the soil where large roots were absent as a result of grubbing (by which we name artificial uprooting of stumps of trees left after cutting). Charcoal was not attested in either of the two arable horizons. However, charcoals dating to 905 ± 80 cal. BP (IGSB-1775) were found in a pit No 9, which was dug in the lower part of the slope (30 m from the edge of the swamp). We suggest that these charcoal fragments were transferred down by water after a burning (or a fire) in the upper part of the slope, where the profile 8 was located. It is hard to judge whether the fire was related to a clearing.

The possible history of this place could be the following: trees had been cut and grubbed, small amount of woods had been burnt and soil had been plowed whereas charcoal had been partly transported by water down the slope. Assumptions that the plowing had taken place after felling and grubbing of trees, was confirmed by the analysis of ancient root channels.

The root channel rc1 (Fig. 2, Table 2) began from the upper arable layer and penetrated the lower one; this meant that the tree had grown between periods of plowing. Upper parts of the root channels rc 2 to rc 6 adjoined the lower arable layer. Roots that formed the rc2, 3, 5 and 6 had been most likely pulled from the soil as a result of grubbing: partial destruction of the channel edge was visible in the upper part of the layer; the channels were filled with relatively large lumps of soil material, which looked like spots (Fig. 3d and e). In the channels rc2 (Figs. 3d), 5 (Fig. 3e) and 6, there was also a whitish material *albic* which had once been probably located in the upper layer of the soil, but it was absent from the upper layers at the time of the study. The root channel rc4 was composed of ferruginous root pseudomorph which was formed by organic material of the root. Most likely, the tree had been felled and the root had remained in the soil.

Charcoals dating from 995 ± 65 cal years BP (the charcoal sample 2–1) were found inside the rc 2 (Fig. 3d). Most likely, the charcoal had been on surface of the soil after burning for clearing and then had spilled into the root channel immediately after pulling the root during

Table 4
Radiocarbon dates for charcoals from the Meshchera Lowlands calibrated according to Reimer et al. (2013) using IntCal13.

Site	Pit	Sample	Depth, cm	Matter	Lab. code	Lab. radiocarbon age (BP)	Cal. radiocarbon age (BP)	Cal. BC/AD
1	1	1–1	20	Charcoal	IGSB-1773	1145 ± 60	1075 ± 75	875 ± 75 AD
1	4	1–4	4–10	Charcoal	IGSB-1784	245 ± 60	280 ± 125	1670 ± 125 AD
1	6	1–6	4–8	Charcoal	IGSB-1783	130 ± 50	140 ± 105	1810 ± 105 AD
2	8	2–1	25–30	Charcoal	IGSB-1774	1065 ± 70	995 ± 65	955 ± 65 AD
2	9	2–2	10–15	Charcoal	IGSB-1775	1000 ± 70	905 ± 80	1050 ± 80 AD
3	10	3–1	4–24	Charcoal	IGSB-1777	1015 ± 70	920 ± 85	1030 ± 85 AD
3	10	3–2	20–35	Charcoal	IGSB-1776	1395 ± 70	1315 ± 55	635 ± 55 AD
3	10	3–5	35–45	Charcoal	IGSB-1778	2205 ± 75	2210 ± 90	260 ± 90 BCE
3	12	3–8	14–17	Charcoal	IGSB-1779	485 ± 70	530 ± 70	1420 ± 70 AD
4	13	4–1	4–15	Charcoal	IGSB-1780	2150 ± 70	2165 ± 110	215 ± 110 BCE
4	14	4–2	20–25	Charcoal	IGSB-1781	2610 ± 80	2670 ± 125	720 ± 125 BCE
4	15	4–3	4–8	Charcoal	IGSB-1782	50 ± 30	55 ± 80	1895 ± 80 AD

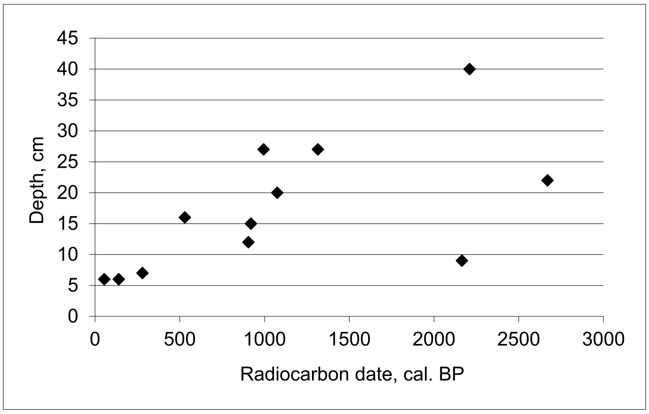

Fig. 6. Radiocarbon dates and depth of charcoal sampling.

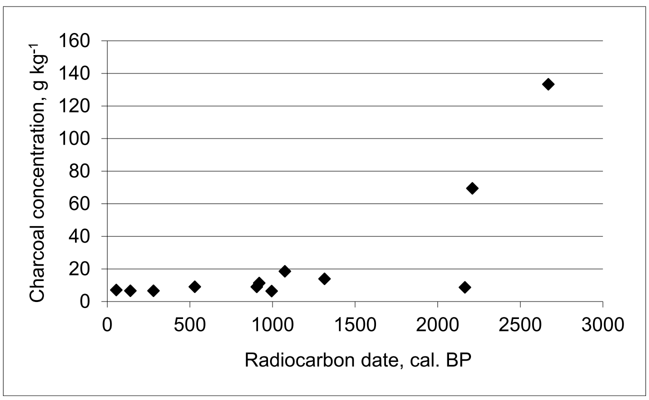

Fig. 7. Radiocarbon dates and charcoal concentration.

the grubbing. The age interval of the charcoal intersected with the age of the charcoal sample IGSB-1775. Possibly both these samples had been formed in one moment of burning wood for plowing. The difference in the age of charcoal fragments was small and could be caused by the different ages of the burned trees.

A pattern of one tree uprooting was clearly distinguishable in the profile: the pattern of an ancient pit about 80 cm deep was most clearly seen on the wall of the soil profile (Fig. 2, Profile 8, t-pit1 and Fig. 3h). The front of the pit was filled with a relatively dark material Bhs. The material of the upper soil layer usually moves to the front part of the pit when a tree falls with uprooting (Bobrovsky and Loyko, 2016). Later this upper soil material had been changed probably because of the agricultural use; in the time of the study there was no such material in the upper (and any other) parts of the soil. Three more root channels rc7, 8 and 9 were also clearly distinguishable in the profile. All these root channels were relatively large in their diameters and they were filled with light material Bhs & E. In the remaining part (above tl), the profile was represented by a patchy pattern, in which it was difficult to distinguish the boundaries of possible pits. It could be assumed that there was also a pit (t-pit 2). Spotting in the soil was observed to a depth of more than 115 cm where the lower boundary of tl was located.

4.5.3. Site 3, profile 10

In the upper part of the profile, there was an arable horizon al of very small thickness with an even bottom line (Fig. 2, Table 2). The horizon was sufficiently homogenized, but not evenly humusified; signs of the original mineral material were preserved (different variants of Bhs, Bs and E in some places). Such patterns usually occur after the cultivation of soil by loosening tools (an ard or wooden plow) in the absence of fertilizer (manuring) (Bobrovsky, 2010). Charcoals were found in some spots where they were mixed with the material of the A horizon. The age of the charcoals was 920 ± 85 cal. BP (sample 3–1). There were two most noticeable patterns which were deeper than the humus horizon: a large root channel (rc1) and a pit of the ancient treefall (t-pit). We assume that the root channel (Fig. 2, Profile 10, rc1 and Fig. 3f) was formed as a result of the grubbing of a relatively large tree, most likely *Pinus sylvestris*. A partial destruction of the upper edge of the root channel was clearly visible; the channel was filled with large clumps of mineral soil. A significant part of the material was *albic*; the majority of charcoal fragments were located in the upper part of the rc1. The age of these charcoals (sample 3–2) was greater than that of charcoals taken from the horizon A: they dated 1315 ± 55 cal. BP. Therefore, we could assume that forest had been burnt, cut and grubbed before an agricultural use of the site.

A pattern of the pit of the ancient tree-uprooting was visible on several walls of the soil profile (Figs. 2 and 3f). The pit was filled with bright mineral materials, such as Bhs, Bs and E. A very large quantity of charcoals was found in the pit. In Fig. 2 (Profile 10), we can see that two layers of charcoals were separated by a layer of mineral soil; these charcoal layers were beginning to join when digging the profile wall sideways. *Albic* and yellowish red, very pale brown Bhs/Bs material adjoined the accumulations of charcoal fragments. The age of the charcoals was 2210 ± 90 cal. BP that was almost a thousand years more than the age of charcoals in the root channel rc1. Overturned material was attested up to 1 m and deeper in the profile. The root channel rc2 was clearly discernible.

In the pit 12 located downslope relative to the Profile 10, next to an oligotrophic bog, a layer of charcoals and peated material was described, above which there was a layer of mineral soil. The profile structure was typical for the colluvial deposits. We assume that charcoals and mineral material had been transported by a sheet-wash from the slope and the top of the hill. The age of the charcoals was 530 ± 70 cal. BP that was less than the age of charcoals in the Profile 10, including in the old-arable horizon. These charcoals fragments could have been formed as a result of a fire or as a result of a forest burning for agriculture.

4.5.4. Site 4, profile 13

In the upper part of the profile, ancient arable horizon A (Fig. 2, Profile 13, al; Table 2) was located. The horizon was very small in thickness and had the even bottom line that was visible on the “greater” length of the layer. The horizon was well homogenized. Charcoals were met by light clusters inside the horizon A. The age of the charcoals was 2165 ± 110 cal. BP. Such ancient charcoals are most likely not related to agriculture. Probably charcoals after an ancient fire had been transferred into a pit of a small treefall, and then this material had been involved in plowing. However, there was no evidence for such an assumption. The structure of the horizon A indicated that it had been formed rather recently: colour of the horizon was significantly different from the underlying horizon E; the horizons were nowhere to be implicated; and material of the A horizon did not occur in the root channels. In the Pit 15 located near the Profile 13, the age of charcoals from the same horizon on the contrary was relatively small: it was 55 ± 80 cal. BP.

In the horizon E there were traces of many pedoturbations, almost all of this horizon was represented by spots (lumps). Such pedoturbations could appear as a result of either treefalls with very small pit depths, or mixing the soil during the grabbing of small trees. The bottom line of the horizon E consisted of many semicircular patterns, which are formed after small treefalls, as well as from small tongues, most of which continued root channels in the form of ferruginous root pseudomorphs (Fig. 2, Profile 13 and Fig. 3g). We assume that the most likely impact on this site had been felling and grabbing of small trees in order to use the site for agriculture.

In the middle and lower part of the profile, up to 125 cm and deeper in some places, there were material Bs and Bts with spots which usually result from soil mixing by tree-uprooting. We could distinguish a contour of one of the old pits (t-pit in Fig. 2).

In Site 4, a well-discernible pit of an old tree-uprooting with a large amount of charcoals (similar to the t-pit in Profile 10 of Site 3) was described in the pit 14. The age of charcoal samples was 2670 ± 125 cal. BP (sample 4–2). These charcoals were the oldest among all other soil charcoals studied in the area.

Thus, in Site 1, all charcoal fragments were associated with the arable layers; in Sites 2 and 3 they were also associated with arable layers and additionally with root channels and pits formed after treefalls with uprooting; in Site 4 charcoal fragments were associated with plowing and tree-uprooting. In profile 10 in Site 3, attested charcoals were associated with all three factors of pedoturbation.

5. Discussion

5.1. Pedoturbations and stratigraphy of charcoals in the soil

The presence of charcoals inside mineral soil is always an evidence for pedoturbation, if it is not deluvial, alluvial, or eolian deposits. In about half of the studied cases, charcoals were found in arable layer at a depth of up to 20 cm (Fig. 4, Table 3). Charcoals could appear in arable layer when a soil which contained charcoal was plowed. However, in our opinion, this was generally a rare phenomenon (possibly observed in the pit 4–2). A more likely situation was that charcoals appeared in the arable layer when a forest had been burnt before soil cultivation, which could be either a single clearing of the plot to make it a permanent arable land, or periodical clearing under shifting and slash-and-burn agricultural systems. In such cases, moving of charcoals into the soil was a result of soil scuffing and mixing by arable tools: usually, by an ard or a wooden plow. Normally, a plow or an ard could treat the soil to the depth of 8–12 cm (Bobrovsky, 2010). In the investigated profiles, the depth of treatment was 6, 10, 11, 14 and 17 cm (Table 2). Cultivation of soil by an ard or a wooden plow had a scuffing character, so quite a long time was necessary to form a homogeneous arable horizon. During plowing, charcoal was crushed and destroyed, so presence of a significant number of relatively large charcoal fragments inside an arable layer indicates a relatively small number of plowing events in the studied plots. Another sign of a short plowing time is an incomplete homogenization of the arable layer material. For example, in site 3, the colour of patterns of the arable layer was the same as the colour of the lower horizon. Charcoals could be preserved during the plowing, if a depth of the plowing had decreased (after the initial penetration of charcoals into the soil), and this can be seen in Site 1.

Besides the arable layers, charcoals were found in root channels. With the gradual decomposition of dead roots, the released volume of “the container” was filled with mineral particles, since they were much smaller than charcoals. Therefore charcoals could not move to root channels over time, but they could get to these channels with a sharp pulling out of the roots during an artificial or natural uprooting (grubbing or windfall, respectively). In all observed cases, the form and filling of root channels, inside which the charcoals occurred, corresponded to the pattern of grubbing. All this suggests that charcoals within the root channels originated from a burning before plowing.

After arable layers and root channels, the third type of patterns, where charcoals were attested in our study, were ancient pits after treefalls with uprooting. Previous studies (Gavin, 2003; Gavin et al., 2003a; Talon et al., 2005; Sanborn et al., 2006) reported on the leading role of treefalls for burial of charcoals in soils. Charcoals can move deep enough into a pit when a tree falls with uprooting and rotation: the clod of earth with the roots turns and the roots are torn off; as a result, the tree trunk slides back into the pit. This type of treefall is called rotational treefall (Beatty and Stone, 1986), complex uprooting (Schaetzl et al., 1989b), ball-and-socket windthrow (Allen, 1992), or « complete treefall, with the tree stump tilted vertically but completely situated within the original micro-depression» (Langohr, 1993). *Pinus sylvestris,* which was common in the study area, usually falls with such rotation, moving charcoals from the surface of the soil and from the upper soil horizons into the pit formed by uprooting. Charcoals are often located at the bottom of a pit; however, charcoal translocation into the pit can be preceded by a deposition of a considerable volume of soil from the hillock formed by roots. As a result, charcoals or their accumulations can be separated by layers of mineral soil, as we saw in the profile 10 (Figs. 2 and 3i, Table 2). Totally in our study, about 20% of charcoal samples were taken from pits of ancient treefalls from a depth 25–45 cm.

One of the problems associated with a diagnosis of ancient events is a possibility that charcoals that are located in one pattern can arise from several fire events which occurred at different times. However, when charcoal fragments are spatially located in clusters, i.e. are not scattered, it is most likely that the charcoals in one cluster took their origin from the same fire event, as their transport into one cluster after several fire events is very unlikely. This assumption was also expressed by Lertzman et al. (2002) and further confirmed by results of Gavin et al. (2003b) which showed that radiocarbon dates were very similar for charcoal fragments from the same stratigraphic layer. For our study, we also assumed that in one sample there were charcoals of the close age from the same fire event.

Many authors report the uneven distribution of charcoals along the depth of a profile: a part of charcoals is usually located in the upper layer and the other part deeper than 30–40 cm (Carcaillet, 2001; Francis and Knowles, 2001). We suggest such differences in the depth are caused by different paths of charcoal immersion into the soil. For example, after soil plowing, the depth of charcoal locations is usually rather small; however after treefalls, the depth of charcoal location can reach 30 and even 80 cm (the last we observed on sandy soils in the west of Central Russian Upland in the Kaluga region). In our study, in ancient pits charcoals most often occurred at a depth of 40 cm and maximum charcoal concentration up to 133 g/kg was there observed.

There is an opinion that charcoal in soil becomes more fragmented over time (Feiss et al., 2017). However, according to our observations, the degree of fragmentation of charcoals was strongly associated with factors conditioning charcoal translocation into the soil. In arable layers, charcoals had been subjects of repeated impacts of plowing and thus they were maximally fragmented. In the lower parts of arable layers, charcoals were less fragmented probably due to a decrease in the depth of tillage during subsequent plowing. In root channels and in pits formed after treefalls, charcoals of various sizes occurred. And only in ancient pits after treefalls we could find accumulations of large charcoal fragments (sometimes up to several cm in size as we saw in the profile 10). We assume that the grinding of charcoals attested in root channels and in ancient pits had mainly happened before or during treefalls, because factors affecting size of charcoals seems to be weak inside well-drainage sandy soils.

5.2. Taxonomic composition and age of charcoals in comparison with the results of peat sediments analysis; frequency of fire events

Taxonomic composition of charcoals in the studied soil pits was extremely poor: *Pinus* charcoals of different age prevailed, that means dominating of *Pinus sylvestris* in vegetation for a long time. According to the polen data in the study region, from about 8000 years BP, broad-leaved and *Pinus sylvestris* forests were widely distributed (Novenko et al., 2016). Among trees *Betula*, *Pinus*, *Quercus*, *Tilia*, *Ulmus*, and *Alnus* were common; *Fraxinus* and *Salix* also occurred. Approximately from 2600 years BP *Picea* became more frequent (Novenko et al., 2016). Most of these taxa are common in the region till now; *Pinus* always is abundant, while *Tilia* is greatly reduced, and *Ulmus* and *Fraxinus* nearly disappeared.

The discrepancy between the richness of species composition according to palynological data and extreme poverty according to pedoanthracology data can be explained only partially. The studied sites represent combinations of depressions and well drained patches on elevations where *Pinus* could dominate for millennia. Due to a relatively large biomass of pines, the probability of finding their charcoals is much higher than that of other species. High proportion of *Pinus* in the vegetation had to be supported by frequent fires in the region that is confirmed by analysis of charcoal layers from five peatlands (Novenko et al., 2016; Dyakonov et al., 2017): charcoal layers were mainly formed during the periods 8500–4500 and 3500–2000 cal. BP; periods between fire events varied from 30 to 80 years in that time. We registered the oldest fire events in Sites 3 and 4 (Fig. 4, Table 4; samples 3–5, 4–1 and 4–2). Most likely these events were closed in time or even it was the same fire event, because the discrepancy in time between samples may be due to the relatively long lifespan of *Pinus* that leads to an "inbuilt age" effect (Gavin et al., 2003a).

According to charcoal record in peatlands, the last 2000 years in the region were characterized by a decline in fire frequency, which was likely caused by a decrease in forested areas in favour for agriculture land. However, fire events recorded in soil became more abundant at this point. A fire event around 1400 cal. BP was registered in Site 3 and several fire events around 1000 cal. BP (or the same event) were registered in Sites 1, 2 and 3. Another four charcoal samples from Sites 1, 3 and 4 were 500 cal. BP or less. Thus, there is a discrepancy between the ages of charcoals in the studied soils and the ages of the charcoal layers in the surrounding peatlands.

We can offer several explanations for the fact that charcoal almost simultaneously sharply decreased in the peatlands and began to occur in the soil. Between 2000 and 1400 cal. BP a decrease in forest cover and an increase in the proportion of grass communities are found in the region. Since 1400 cal. BP, numerous indicators of anthropogenic activity have appeared, such as cereal pollen (mainly *Secale cereale*), pioneer species which are typical for agricultural lands, human settlements and disturbed habitats, such as *Centaurea cyanus, Plantago major-type, Plantago lanceolata, Rumex* spp., *Convolvulus* spp., *Polygonum aviculare, Ranunculus acris*) (Novenko et al., 2016). According to archaeological data, the start of widespread farming in the region is attributed to the early Iron Age (Archeological map …, 1999), which would be a starting point of active burning for agriculture in the area.

Before agriculture became abundant, predoturbation, the main factor controlling charcoal accumulation in soil, had been much less efficient; they had only been controlled by natural events (first of all, tree falls with uprooting). Charcoals remaining on the surface of mineral soil could escape accumulation. Combustion in repeated fires is probably the main cause of charcoal loss (Czimczik et al., 2005; Schmidt and Preston, 2006). Another important factor of charcoals loss on raised relief positions is their transport into lower positions by water and wind (Tinner et al., 2006): the hydrophobicity of charcoals ensures the easiness of their transfer. Soil erosion after fires can also be accompanied by solifluction leading to almost complete destruction of the upper soil layer on slopes (Gobet et al., 2003; Lespez, 2003). As a result, between 8000 and 2000 years BP, if fires were more frequent than pedoturbation events, accumulation of charcoal in soil was primarily controlled by pedoturbation rates. Additionally, *Pinus sylvestris* with a deep and powerful root system dominated the forest in the area. Pines usually survive a ground fire and do not fall after the fire, increasing the chance of a time gap between fire events and pedoturbations. According to peatland charcoal record, fires were quite abundant between 8000 and 2000 years BP that rather decreased litter accumulation rates, reducing potential material for charcoal formation. When agriculture had begun in the area, predoturbation events became much more regular, grubbing and plowing followed the burning immediately and ensured deep penetration of charcoals into the soil, providing opportunities for charcoal accumulation observed in the area starting from 2000 cal. BP.

6. Conclusion

Sandy soils of the Meshchera Lowlands contain important amounts of charcoals which can be used as a paleo-archive of ecological data. In the study area, charcoals were unevenly distributed both horizontally and vertically in the soil profiles. Important factors determining the charcoal presence and spatial structure of their distribution within the soil (including the depth) were natural and anthropogenic pedoturbations. Soil morphological analysis allowed to reveal patterns in the soil profile and to assume types of pedoturbation which had conditioned formation of these patterns. In this study, we discussed the following soil patterns: arable horizons, root channels, and pits formed by ancient treefalls with uprooting.

We suggest to associate forming and translocation of charcoals in soil with a certain stage of the ecosystem history, if charcoals are localized in some patterns which were caused by plowing, natural or artificial uprooting and other events leading to pedoturbations. In our study, for most charcoal samples, we observed a reliable correlation of charcoal occurrence with burning for clearing and subsequent plowing. These activities had provided the upper layer of the soil (arable layers and sometimes root channels) with charcoal fragments. The largest and most abundant charcoals were located at the greatest depths of ancient pits formed after treefalls with uprooting. In arable horizons, fine pieces of charcoal often occurred, because each subsequent plowing more and more had crushed charcoals, whereas charcoal pieces located in pits of ancient tree-uprooting did not change with time in their size in condition of well-drainage sandy soils. Older charcoals mostly occurred in ancient pits originating by tree uprooting, and younger charcoals were more associated with arable horizons. We explain this by a change from natural to artificial pedoturbations within the landscape, i.e. by a transition from free forest development (before active anthropogenic impacts) to forest clearing by man (felling and grubbing of relatively small trees) for agriculture.

Periods of charcoal accumulation in peatlands and in soil did not coincide during the last several millennia in the study region: since 2000 cal. BP the supply of charcoal in the peatlands had decreased and approximately from this time translocation of charcoal into mineral soil had begun. We associate this with the changing dynamics of landscapes under the influence of anthropogenic factors.

Our study shows that combination of methods of pedoanthracology and soil morphology provides valuable information complementing palynological studies of ecosystem history.

Funding sources

Data sampling, taxonomic identification of charcoal samples and preparation of the article were supported by a grant from the Russian Science Foundation (Grant 16-17- 10045). Radiocarbon dating was supported by a project 15-04-03170 from the Russian Foundation for Basic Research (RFBR). Data analysis was supported by a project 18-04-01329 from the RFBR.

Acknowledgements

We thank Dr. Lyudmila Shumilovskikh for consultations in soil charcoal identifications. We also thank two anonymous reviewers for the valuable questions and comments which helped us to improve the manuscript.

References

Abramova, T.A., 1999. Antropogennoye vozdeystviye na landshafty tsen-tral'noy Meshchery v golotsene (po palinologicheskim dannym) [Human impact on the landscapes of Central Meshchera a in the Holocene (by palynological data)], Vestnik MSU. Series 5. Geography 1, 47–51 (in Russian).

Adámek, M., Bobek, P., Hadincová, V., Wild, J., Kopecký, M., 2015. Forest fires within a temperate landscape: a decadal and millennial perspective from a sandstone region in Central Europe. For. Ecol. Manag. 336, 81–90.

Agnoletti, M., Anderson, S. (Eds.), 2000. Forest history: International Studies on Socio-economic and forest Ecosystem Change. Report N 2 of the IUFRO Task Force on Environmental Change. CABI Publishing.

Allen, J.R.L., 1992. Trees and their response to wind: mid Flandrian strong winds, Severn

Estuary and inner Bristol Channel, southwest Britain. Philos. Trans. R. Soc. Lond. B Biol. Sci. 338 (1286), 335–364.
Annenskaya, G.N., Mmay, I.I., Tseselchuk, YuN., 1983. Landscapes of the Ryazan Meshchera and Possibilities of Their Development. [Landshafty Ryazanskoĭ Meshchery I Vozmozhnosti Ih Osvoeniya] M.: Izd-vo MGU, 246 C.
Archeological map of Russia, 1999. In: Krasnov, YuA. (Ed.), Ryazan' Region, Part 1. Institute of archeology RAS–pres, Moscow (in Russian).
Armson, K.A., Fessenden, J., 1973. Forest windthrow and their influence on soil morphology. Soil Sci. Soc. Am. Proc. 37, 781–783.
Beatty, S.W., Stone, E.L., 1986. The variety of soil microsites created by tree falls. Can. J. For. Res. 16 (3), 539–548.
Benkova, V.E., Schweingruber, F.H., 2004. Anatomy of Russian Woods. An Atlas for the Identification of Trees, Shrubs, dwarf Shrubs and Woody Lianas from Russia. Bern, Etc. Haupt Verlag.
Bobrovsky, M.V., 2010. Lesnye Pochvy Evropeyskoy Rossii: Bioticheskie I Antropogennye Faktory Formirovaniya [Forest Soils of European Russia: Biotic and Anthropogenic Factors of Formation]. KMK, Moscow (in Russian).
Bobrovsky, M., Loyko, S., 2016. Patterns of pedoturbation by tree uprooting in forest soils. Russ. J. Ecosys. Ecol. 1 (1), 1–22.
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.
Carcaillet, C., Perroux, A.S., Genries, A., Perrette, Y., 2007. Sedimentary charcoal pattern in a karstic underground lake, Vercors massif, French Alps: implications for palaeo-fire history. Holocene 17 (6), 845–850.
Carcaillet, C., Talon, B., 1996. A view of the wood charcoal stratigraphy and dating in soil: a case study of some soils from the French Alps. Géogr. Phys. Quaternaire 50 (2), 233–244.
Carcaillet, C., Thinon, M., 1996. Pedoanthracological contribution to the study of the evolution of the upper treeline in the Maurienne Valley (North French Alps): methodology and preliminary data. Rev. Palaeobot. Palynol. 91 (1–4), 399–416.
Clark, J.S., 1988. Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. Quat. Res. 30, 67–80.
Clark, J.S., Lynch, J., Stocks, B.J., 1998. Relationships between charcoal particles in air and sediments in westcentral Siberia. Holocene 8, 19–29.
Cunill, R., Soriano, J.M., Bal, M.C., Pèlachs, A., Pérez-Obiol, R., 2012. Holocene treeline changes on the south slope of the Pyrenees: a pedoanthracological analysis. Veg. Hist. Archaeobotany 21 (4–5), 373–384.
Czimczik, C.I., Schmidt, M.W.I., Schulze, E.D., 2005. Effects of increasing fire frequency on black carbon and organic matter in Podzols of Siberian Scots pine forests. Eur. J. Soil Sci. 56 (3), 417–428.
de Lafontaine, G., Asselin, H., 2011. Soil charcoal stability over the Holocene across boreal northeastern North America. Quat. Res. 76 (2), 196–200.
Dearing, J.A., Battarbee, R.W., Dikau, R., Larocque, I., Oldfield, F., 2006. Human–environment interactions: learning from the past. Reg. Environ. Change 6 (1). https://doi.org/10.1007/s10113-005-0011-8.
Dyakonov, K., Novenko, E., Mironenko, I., Kuprijanov, D., Bobrovsky, M., 2017. The role of fires in the Holocene landscape dynamics of the southeastern part of Meshchera lowlands. Dokl. Earth Sci. 477 (1), 1336–1342.
Dyakonov, K.N., Abramova, T.A., 1998. Itogi paleolandshaftnykh issledovaniy v Tsentral'noy Meshchere [The results of paleolandscape researches in Central Meshchera]. Proc. Roy. Geogr. Soc. 130 (4), 10–21 (in Russian).
Embleton-Hamann, C., 2004. Processes responsible for the development of a pit and mound microrelief. Catena 57, 175–188.
Feiss, T., Horen, H., Brasseur, B., Lenoir, J., Buridant, J., Decocq, G., 2017. Optimal sampling design and minimal effort for soil charcoal analyses considering the soil type and forest history. Veg. Hist. Archaeobotany 26 (6), 627–637.
Foster, D., Swanson, F., Aber, J., Burke, I., Brokaw, N., Tilman, D., Knapp, A., 2003. The importance of land-use legacies to ecology and conservation. AIBS (Am. Inst. Biol. Sci.) Bull. 53 (1), 77–88.
Francis, J.K., Knowles, O.H., 2001. Age of A2 horizon charcoal and forest structure near Porto Trombetas, Pará, Brazil. Biotropica 33 (3), 385–392.
Gavin, D.G., Brubaker, L.B., Lertzman, K.P., 2003a. An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. Can. J. For. Res. 33 (4), 573–586.
Gavin, D.G., Brubaker, L.B., Lertzman, K.P., 2003b. Holocene fire history of a coastal temperate rain forest based on soil charcoal radiocarbon dates. Ecology 84 (1), 186–201.
Gavin, D.G., 2003. Forest soil disturbance intervals inferred from soil charcoal radiocarbon dates. Can. J. For. Res. 33 (12), 2514–2518.
Gobet, E., Tinner, W., Hochuli, P.A., van Leeuwen, J.F.N., Ammann, B., 2003. Middle to late Holocene vegetation history of the upper engadine (swiss alps): the role of man and fire. Veg. Hist. Archaeobotany 12, 143–163.
Henkner, J., Ahlrichs, J.J., Downey, S., Fuchs, M., James, B.R., Knopf, T., Scholten, T., Teuber, S., Kühn, P., 2017. Archaeopedology and chronostratigraphy of colluvial deposits as a proxy for regional land use history (Baar, southwest Germany). Catena 155, 93–113.
Hole, F.D., 1961. A classification of pedoturbation and some other processes and factors of soil formation in relation to isotropism and anisotropism. Soil Sci. 91, 375–377.
Hultberg, T., Gaillard, M.J., Grundmann, B., Lindbladh, M., 2015. Reconstruction of past landscape openness using the Landscape Reconstruction Algorithm (LRA) applied on three local pollen sites in a southern Swedish biodiversity hotspot. Veg. Hist. Archaeobotany 24 (2), 253–266.
Ivanov, A.N., 1995. Mire geosystems of central Meshchera, vestnik MSU. Series 5. Geography 5, 86–94 (in Russian). [Bolotnye ehkosistemy Central'noj Meshchery].
IUSS Working Group, 2015. World reference base for soil resources 2014 (update 2015), international soil classification system for naming soils and creating legends for soil maps. World Soil Resour. Rep. 106.
Jansen, D., Lungershausen, U., Robin, V., Dannath, Y., Nelle, O., 2013. Wood charcoal from an inland dune complex at Joldelund (Northern Germany). Information on Holocene vegetation and landscape changes. Quat. Int. 289, 24–35.
Kasin, I., Ellingsen, V.M., Asplund, J., Ohlson, M., 2016. Spatial and temporal dynamics of the soil charcoal pool in relation to fire history in a boreal forest landscape. Can. J. For. Res. 47 (1), 28–35.
Kirby, K., Watkins, C. (Eds.), 1998. The Ecological History of European forest. University press, Cambridge 1998.
Langohr, R., 1993. Types of Tree Windthrow, Their Impact on the Environment and Their Importance for the Understanding of Archaeological Data Helinium, pp. 36–49 XXXIII(1).
Larsen, A., Robin, V., Heckmann, T., Fülling, A., Larsen, J.R., Bork, H.R., 2016. The influence of historic land-use changes on hillslope erosion and sediment redistribution. Holocene 26 (8), 1248–1261.
Leopold, M., Völkel, J., 2007. Colluvium: definition, differentiation, and possible suitability for reconstructing Holocene climate data. Quat. Int. 162, 133–140.
Lertzman, K., Gavin, D., Hallett, D., Brubaker, L., Lepofsky, D., Mathewes, R., 2002. Long-term fire regime estimated from soil charcoal in coastal temperate rainforests. Conserv. Ecol. 6 (2), 5.
Lespez, L., 2003. Geomorphic responses to long-term land use changes in Eastern Macedonia (Greece). Catena 51, 181–208.
Moser, D., Di Pasquale, G., Scarciglia, F., Nelle, O., 2017. Holocene mountain forest changes in central Mediterranean: soil charcoal data from the Sila Massif (Calabria, southern Italy). Quat. Int. 457, 113–130.
Nelle, O., Robin, V., Talon, B., 2013. Pedoanthracology: analysing soil charcoal to study Holocene palaeoenvironments. Quat. Int. 289, 1–4.
Novák, J., Abraham, V., Houfková, P., Kočár, P., Vaněček, Z., Peška, J., 2018. History of the Litovelské Pomoraví woodland (NE Czech Republic): a comparison of archaeo-anthracological, pedoanthracological, and pollen data. Quat. Int. 463 (B), 352–362.
Novák, J., Sádlo, J., Svobodová-Svitavská, H., 2012. Unusual vegetation stability in a lowland pine forest area (Doksy region, Czech Republic). Holocene 22 (8), 947–955.
Novenko, E.Yu, Tsyganov, A.N., Volkova, E.M., Kupriyanov, D.A., Mironenko, I.V., Babeshko, K.V., Utkina, A.S., Popov, V., Mazei, YuA., 2016. Mid- and Late Holocene vegetation dynamics and fire history in the boreal forest zone of European Russia: a case study from the south-eastern part of Meschera Lowlands. Palaeogeogr. Palaeoclimatol. Palaeoecol. 459, 570–584.
Pawlik, Ł., Phillips, J.D., Šamonil, P., 2016. Roots, rock, and regolith: biomechanical and biochemical weathering by trees and its impact on hillslopes – a critical literature review. Earth Sci. Rev. 159, 142–159.
Pawlik, Ł., Musielok, Ł., Migoń, P., Wrońska-Wałach, D., Duszyński, F., Kasprzak, M., 2017. Deciphering the history of forest disturbance and its effects on landforms and soils–lessons from a pit-and-mound locality at Rogowa Kopa, Sudetes, SW Poland. Bull. Geography. Phys. Geogr. Ser. 12 (1), 59–81.
Phillips, J.D., Šamonil, P., Pawlik, Ł., Trochta, J., Daněk, P., 2017. Domination of hillslope denudation by tree uprooting in an old-growth forest. Geomorphology 276, 27–36.
Ponomarenko, E.V., 1999. Metodicheskiye podkhody k analizu suktsesionnykh protsessov v pochvennom pokrove [Methodological approaches to analysis of succession processes in soil cover]. In: Smirnova, O.V., Shaposhnikov, E.S. (Eds.), Suktsessionnyye Protsessy V Zapovednikakh Rossii I Problemy Sokhraneniya Biologicheskogo Raznoobraziya [Succession Processes in Reserves of Russia and Problems of Biological Diversity Preservation]. Russian Botanical Society, Saint-Petersburg, pp. 34–57 (In Russian).
Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves, 0–50,000 Years cal BP. Radiocarbon 55, 1869–1887.
Reitalu, T., Kuneš, P., Giesecke, T., 2014. Closing the gap between plant ecology and Quaternary palaeoecology. J. Veg. Sci. 25 (5), 1188–1194.
Reitalu, T., Seppä, H., Sugita, S., Kangur, M., Koff, T., Avel, E., Kihno, K., Vassiljev, J., Renssen, H., Hammarlund, D., Heikkilä, M., Saarse, L., Poska, A., Veski, S., 2013. Long-term drivers of forest composition in a boreonemoral region: the relative importance of climate and human impact. J. Biogeogr. 40 (8), 1524–1534.
Robin, V., Knapp, H., Bork, H.R., Nelle, O., 2013. Complementary use of pedoanthracology and peat macro-charcoal analysis for fire history assessment: illustration from Central Germany. Quat. Int. 289, 78–87.
Robin, V., 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. Veg. Hist. Archaeobotany 23 (1), 51–65.
Šamonil, P., Král, K., Hort, L., 2010. The role of tree uprooting in soil formation: a critical literature review. Geoderma 157, 65–79.
Šamonil, P., Schaetzl, R.J., Valtera, M., Golias, V., Baldrian, P., Vasickova, I., Adam, D., Janik, D., Hort, L., 2013. Crossdating of disturbances by tree uprooting: can treethrow microtopography persist for 6000 years? For. Ecol. Manag. 307, 123–135.
Šamonil, P., Valtera, M., Schaetzl, R.J., Adam, D., Vašíčková, I., Daněk, P., et al., 2016. Impacts of old, comparatively stable, treethrow microtopography on soils and forest dynamics in the northern hardwoods of Michigan, USA. Catena 140, 55–65.
Sanborn, P., Geertsema, M., Jull, A.T., Hawkes, B., 2006. Soil and sedimentary charcoal evidence for Holocene forest fires in an inland temperate rainforest, east-central British Columbia, Canada. Holocene 16 (3), 415–427.
Sass, O., Kloss, S., 2015. Distribution of macro charcoal from forest fires in shallow soils of the Northern Alps. J. Soils Sediments 15 (4), 748–758.

Schaetzl, R.J., Burns, S.F., Johnson, D.L., Small, T.W., 1989a. Tree uprooting: review of impacts on forest ecology. Vegetatio 79 (3), 165–176.

Schaetzl, R.J., Johnson, D.L., Burns, S.F., Small, T.W., 1989b. Tree uprooting: review of terminology, process, and environmental implications. Can. J. For. Res. 19 (1), 1–11.

Schaetzl, R.J., Burns, S.F., Small, T.W., Johnson, D.L., 1990. Tree uprooting: review of types and patterns of soil disturbance. Phys. Geogr. 11 (3), 277–291.

Schmidt, M.W.I., Preston, C.M., 2006. Black (pyrogenic) carbon in boreal forests: a synthesis of current knowledge and uncertainties. Biogeosci. Discuss. 3, 211–271.

Smirnova, O.V., Bobrovsky, M.V., Khanina, L.G., Zaugolnova, L.B., Shirokov, A.I., Lugovaya, D.L., Korotkov, V.N., Spirin, V.A., Samokhina, T.Yu, Zaprudina, M.V., 2017. Hemiboreal forests. In: Smirnova, O.V., Bobrovsky, M.V., Khanina, L.G. (Eds.), European Russian Forests. Their Current State and Features of Their History. Springer, Netherlands, pp. 209–336.

Talon, B., 2010. Reconstruction of Holocene high-altitude vegetation cover in the French southern Alps: evidence from soil charcoal. Holocene 20 (1), 35–44.

Talon, B., Payette, S., Filion, L., 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. Quat. Res. 64, 36–43.

Tinner, W., Hofstetter, S., Zeugin, F., Conedera, M., Wohlgemuth, T., Zimmermann, L., Zweifel, R., 2006. Long-distance transport of macroscopic charcoal by an intensive crown fire in the Swiss Alps-implications for fire history reconstruction. Holocene 16 (2), 287–292.

Touflan, P., Talon, B., Walsh, K., 2010. Soil charcoal analysis: a reliable tool for spatially precise studies of past forest dynamics: a case study in the French southern Alps. Holocene 20 (1), 45–52.

Valtera, M., Schaetzl, R.J., 2017. Pit-mound microrelief in forest soils: review of implications for water retention and hydrologic modelling. For. Ecol. Manag. 393, 40–51.

Velichko, A.A., Kremenetski, K.V., Negendank, J., Mingram, J., Borisova, O.K., Gribchenko, Y.N., Zelikson, E.M., Klimanov, V.A., Novenko, E.Y., Pirumova, L.G., Pisareva, V.V., Razumovski, L.V., Timireva, S.N., 2001. Late Quaternary paleogeography of the north-east of Europe (based on the complex study of the Lake Galich sediments). Russ. Acad. Sci. Izvestiya Ser. Geogr. 3, 42–54 in Russian. [Pozdnechetvertichnaya paleogeografiya severo-vostoka Evropy (po dannym kompleksnogo izucheniya osadkov Galichskogo ozera)//Izvestiya Rossijskoj akademii nauk. Seriya geograficheskaya, izdatelstvo Nauka (M.) 3, s. 42-54].

Vera, F.W.M., 2000. Grazing Ecology and forest History. CABI Publishing, Oxon-New York.

Wood, W.R., Johnson, D.L., 1978. A survey of disturbance processes in archaelogical site formation. Adv. Archaeol. Meth. Theor. 315–370 (N.-Y).