ABS ACTA BIOLOGICA SIBIRICA
A journal on the biodiversity of Siberia and the adjacent lands

Acta Biologica Sibirica 11: 1533–1562 (2025)
doi: 10.5281/zenodo.18029990
http://journal.asu.ru

RESEARCH ARTICLE

Legacies of historical ploughing in the soils of secondary forests, Western Siberia

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Academic editor: A. Matsyura | Received 1 December 2025 | Accepted 20 December 2025 | Published 23 December 2025

http://zoobank.org/42822B8A-8F0D-4FE1-8FE5-04F33423B6A9

Citation: Loiko SV, Kuzmina DM, Istigechev GI, Lim AG, Belkina TN, Kulizhsky SP (2025) Legacies of historical ploughing in the soils of secondary forests, Western Siberia. Acta Biologica Sibirica 11: 1533–1562. https://doi.org/10.5281/zenodo.18029990

Abstract

The abandonment of agricultural land, followed by afforestation, is a widespread global phenomenon. This process is not always well documented. Many ecosystems carry a post-agricultural legacy that is not always obvious, but which can be identified using a series of indicators. One way to identify these indicators is to examine arable soils, the existence of which can be confirmed using archival cartographic information. This study aims to identify morphological indicators of historical ploughing in the soils of secondary forests in southern Western Siberia. The study focused on Luvic Greyzemic Phaeozems that formed on the site of documented peasant arable land abandoned approximately 120–130 years ago. A comprehensive approach combining historical map analysis, field morphological description, laboratory soil analysis and radiocarbon dating of charcoal enabled land-use history to be reconstructed and long-term indicators of former soil ploughing to be identified. These indicators include: a smooth lower boundary of the Ap horizon, its uniform colouration, the presence of agrogenic microrelief (furrows and ridges), the absence of treefall pit-and-mound topography associated with windthrow, and a specific distribution of fine earth particles. The activity of soil fauna (e.g. moles, ants, insects and earthworms) has been shown to be a leading factor in the transformation and masking of these features during post-agrogenic succession. Despite a lengthy recovery period, the soils have not completely returned to a quasi-pristine state. This work provides a methodological foundation for identifying ancient arable lands within forest landscapes in Siberia.

Keywords

Postagrogenic soils, historical land use, indicators of former plowing, residual arable humus horizon, Luvic Greyzemic Phaeozem, Western Siberia, zooturbation

Introduction

The abandonment of agricultural land and subsequent afforestation is a widespread phenomenon in many regions of the world in recent decades, particularly in Europe and Russia. This process is associated with socio-economic changes, urbanisation, declining rural population, reduced agricultural profitability, and shifts in land-use policy (Lyuri et al. 2010; Susyan et al. 2011; Voicu et al. 2017; Nefedova and Medvedev 2020; Nechaeva 2023; Dobrynin et al. 2025).

Between 1700 and 2000, approximately 385–472 million hectares of agricultural land were abandoned worldwide, with forests naturally regenerating on most of these lands, particularly in Europe and eastern North America (Voicu et al. 2017). It is estimated that Russia has 70 million hectares of abandoned agricultural land, half of which is already covered by trees due to natural forest regrowth (Dobrynin et al. 2025).

While the majority of land was abandoned following the dissolution of the Soviet agrarian system, land abandonment had occurred for various reasons even prior to this (Lyuri et al. 2010), resulting in fallow soils significantly older than 100 years (Shopina et al. 2023; Terekhova et al. 2023).

It has been established that the main reason for removing arable land from agricultural use and reducing cultivated areas in Russia is the low profitability of crop production in areas with low natural fertility or degraded land. The cessation of state subsidies in the non-chernozem regions led to a halt in agricultural production. From 2015 to 2025, crop production in Russia stabilised (Rukhovich et al. 2025). Therefore, there is no reason to expect the large-scale emergence of new fallow land. In fact, there is a growing trend of returning previously abandoned land to agricultural use (Nechaeva 2023).

The focus on abandoned lands in environmental science is predicated on the understanding that the cessation of agricultural activity has engendered a number of environmental benefits, including substantial carbon sequestration in post-agrogenic ecosystems (Kurganova et al. 2015).

In addition to the significant impact on the carbon cycle, the sheer extent of abandoned land necessitates the investigation of the ecological consequences within these territories. This is because land-use history exerts a long-term influence on vegetation and soil properties (Verheyen et al. 1999; Dupouey et al. 2002; Brudvig et al. 2013; Yesilonis et al. 2016; Maes et al. 2019; Nikodemus et al. 2022), including through the residual effects of agricultural microtopography (Morrissey and Dietz 2025).

The recognition and understanding of environmental historical legacies facilitates a more comprehensive understanding of contemporary conditions across various levels of organization, ranging from organisms to the global environment. This enhanced understanding reduces the probability of inaccuracies in forecasting or managing future environmental conditions (Foster et al. 2003).

The numerous motives for studying abandoned land soils determine the diversity of approaches to investigating post-agrogenic soils. Researchers most frequently examine the biogeochemical transformation of soils (Bulysheva et al. 2021; Lednev and Dmitriev 2021; Enchilik et al. 2023; Enchilik et al. 2024; Stevenson et al. 2024; Semenkov et al. 2025). There is a paucity of studies on the transformation of morphological patterns at the level of soil morphons (Bobrovsky et al. 2019; Tomson et al. 2021). A highly productive approach is one that integrates not only chemical and morphological methods, but also techniques from soil zoology and forest science (Shopina et al. 2023; Terekhova et al. 2023).

The methodology for assessing the impact of various land-use types and post-agrogenic vegetation successions on soils and soil cover involves the identification of areas with a known land-use history, preferably substantiated by cartographic and historical sources (Loyko et al. 2024; Smirnova et al. 2025). In cases where land abandonment occurred in the 20th century, particularly in its second half, there are typically no difficulties in accurately establishing the fact of former ploughing at the site of a post-agrogenic forest stand. However, for fallows established in the 19th century or earlier, proving the post-agrogenic status of the soil is more challenging. The difficulties arise for at least two reasons.

Firstly, the evidence of previous ploughing becomes less evident over time. Furthermore, given that ploughing in the 19th century disturbed a layer of 10–15 cm or less, compared to 20–30 cm in the 20th century (Khokhlova et al. 2015; Poulton et al. 2024), the initial soil transformation due to cultivation in the 19th century was inherently less profound compared to the alteration of arable soils in the 20th century.

Secondly, historical cartographic sources may be either unavailable or possess low spatial accuracy, exhibiting significant geometric distortions (Ivanov et al. 2022). The demonstration of the historical existence of arable land in heavily forested regions, characterised by limited agricultural development and sparse rural population density, poses a significant challenge. Siberia is an example of a region in which, by the 18th century, a distinct regional pattern of settlement and land use began to form along transportation routes, incorporating pockets of cultivated land (Fedorov 2013).

In order to reliably identify former ploughing under forest cover in such regions, it is necessary to compile regional inventories of indicators of past cultivation. The establishment of these indicators is predicated on the utilisation of areas of soil for which historical ploughing has been cartographically documented. For arable lands abandoned in the 19th century, sources such as village Geometric Plans and Topographic Maps from the 19th and early 20th centuries, held in regional archives and museums of Siberian cities, can be utilised.

The present study addressed the task of identifying signs of historical ploughing in soils under secondary forests in the southern part of the forest zone of Western Siberia. The focus of this study was on former 19th-century peasant arable lands that have since been occupied by secondary birch-pine herbaceous forest, a common feature of this region. The delineation of the former cultivated area was facilitated by the preservation of a Geometric Plan of peasant lands and a topographic map dating to the first half of the 19th century. A further objective of the work was to assess the degree of preservation of the identified features during the spontaneous succession of the forest ecosystem, taking microtopography into account. Our work represents one of the first attempts for abandoned soils and ecosystems in the south-east of Western Siberia to describe the legacy features of relatively old cultivation, dating back more than 120 years.

Materials and methods

Study area

The study was conducted in the northern part of the Tom-Kolyvan Plain, at the contact zone with the levelled areas of cover sand distribution in the Ob-Tom interfluve. The mean annual precipitation is approximately 600 mm, with the majority occurring during the summer months. The mean annual temperature is 0.9 °C, and the average snow cover depth ranges from 60 to 80 cm. The study area is located within the hemiboreal forest zone (subtaiga) (Ermakov 2003). The regional soils are comprised of Luvisols and Greizemic Phaeozems on cover loess-like deposits, as well as Arenosols and Histosols on river terraces and in depressions formed of alluvial sandy deposits with ancient aeolian topography (Dyukarev & Pologova 2011).

The landscape of the study area forms a mosaic of agricultural land, fallows undergoing colonisation by trees and shrubs, and forests dominated by P*inus sylvestris* and *Betula pendula*, with *Populus tremula* being less frequent. A distinct shrub layer, consisting of bird cherry (*Padus avium*), rowan (*Sorbus aucuparia*), honeysuckle (*Lonicera* spp.), and other shrubs, is present in the forests. A well-developed herbaceous layer is also characteristic, consistently comprising several dozen species, with an even greater number of herb species occurring sporadically (Ermakov 2003).

Study plots and research of land use history

The study site was located between the villages of Makurino and Kozhevnikovo in the Yurginsky municipal district of north-western Kemerovo Oblast (Fig. 1). A tract of land on which the now-vanished village of Novo-Makurino was once situated is also located nearby. The selection of this site was made on the basis of the availability of a number of multi-temporal maps and satellite images, thus enabling the reconstruction of land-use history over the past 200 years. The gently sloping plain, devoid of deep depressions, serves to minimise the influence of erosional processes that could otherwise significantly complicate the interpretation of morphological patterns in formerly ploughed soils.

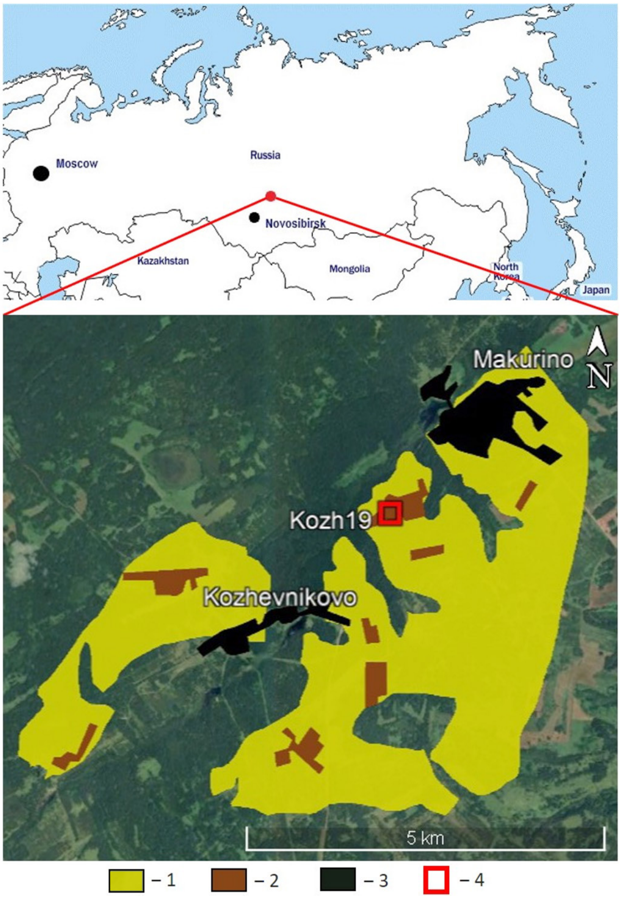

Figure 1. The study area and land according to the Geometric Plan of the village of Kozhevnikovo of 1829: **1** – treeless hayfields, fallow lands and pastures in 1829; **2** – arable lands in 1829; **3** – settlements at the present time; **4** – soil study site.

In order to reconstruct the history of land use between the three villages, the holdings of the State Archive of Altai Krai (Barnaul) were consulted, which contains geometric plans for the landholdings of the aforementioned villages. The maps are contained within Fond 50, which is entitled "The Drawing Office of the Altai Provincial Department of Agriculture and State Property, Barnaul, Barnaul District, Altai Province (1783–1919)". A topographic map created circa 1840, with a scale of 1:42,000, is held at the Russian State Military-Historical Archive (Moscow).

In addition, topographic maps published during the Soviet era, as well as satellite imagery from the CORONA programme spanning from the mid-1960s to the mid-1970s, were also utilised. According to the latter, the village of Novo-Makurino had disappeared by this time. In its final decades, the population of Novo-Makurino specialised in wood processing, which did not support arable farming. Based on this evidence, we estimate the time since plough abandonment at the study site to be 100–120 years.

Ecosystem history was established by examining the oldest early-successional tree species, *Pinus sylvestris* and *Larix sibirica*. Attention was paid to the former crown shape, inferred from the length and arrangement of dead branches along the middle and lower sections of tree trunks. Tree age was determined by increment coring using a Pressler borer. The phytocoenotic conditions at the time of tree establishment were assessed by analysing changes in annual ring width during tree growth. The underlying assumption is that trees establishing in open meadow ecosystems would exhibit small initial increments, followed by a sharp increase and maximum ring widths until canopy closure. Conversely, if pioneer tree species were to establish themselves in a forest that had been selectively logged, resulting in a thinned forest, the increments during the first decades would not be maximal.

Field study methods

In 2019, a total of seven soil profiles were studied. To this end, two soil pits measuring 0.8 x 1/1.5 m, with a depth of 1.2 m, were excavated (Kozh19-1 and Kozh19-2). Two pits, designated Kozh19-3 and Kozh19-4, exhibited dimensions of 0.8 x 1 m and depths of 0.7/1 m, respectively. The two largest soil pits were selected as the primary profiles for the collection of samples, which were subsequently analysed in a laboratory setting.

Profiles 1 and 2 were spatially positioned to characterise the relationship between soil variability and microtopography at metre-scale vertical and hundred-metre-scale horizontal resolutions. The slope gradient was found to be between 2 and 3 degrees. The inclined surface exhibited heterogeneous microtopography. Kozh19-1 (56.02422°N; 84.64367°E) was located on a dispersive, convex microtopographic site. Kozh19-2 (56.02414°N; 84.64339°E) was situated on a concave, convergent depression microtopographic site. This configuration enabled the investigation of the preservation of ploughing features under varying microtopographic conditions. The site featuring concave microtopography demonstrated heightened slope-wash moisture, yet did not undergo groundwater-capillary saturation.

Both sites 1 and 2 were located within the former arable field, retaining the open furrow and upslope ridge morphology formed by historical ploughing. The average ridge height was 8–10 cm. The width of an open furrow together with its adjacent ridge was less than 1 m. The distance between furrows varied from 5 to 15 m, and they were parallel to each other. We hypothesised that the lower boundary of the plough layer might be better preserved beneath the ridges. Consequently, a trench (Kozh19-1(1,2,3)) was excavated at the Kozh19-1 site, traversing an open furrow and an upslope ridge, and also capturing the background soil profile of the Kozh19-1 site. The trench measured 170 centimetres in length and 45 centimetres in depth.

A third soil pit exposed the soil profile at site Kozh19-3 (56.02411°N; 84.64211°E). At this location, the soil experiences groundwater-capillary saturation due to its position on the edge of a closed depression. The profile at site Kozh19-4 (56.02447°N; 84.64183°E) exhibits a microtopographic position analogous to Kozh19-1, yet it occurs within an area distinguished by distinct vegetation. The stand is dominated by Pinus sylvestris, and Abies sibirica is highly abundant in the understorey. The biomass of the herbaceous layer is substantially lower.

The soil profiles were described, and soil groups were determined in accordance with the international World Reference Base (WRB) for Soil Resources classification (IUSS Working Group WRB 2022). The identification of humus forms in the topsoil layer was based on the European system for the functional classification of humus forms (Zanella et al. 2011). From each soil horizon and layer, a 200 g soil sample was collected and placed in a plastic bag. Triplicate samples were obtained from each genetic horizon to ascertain soil bulk density, employing a 4 cm by 4 cm core ring for the purpose. Subsequently, soil and charcoal samples were delivered to the BioGeoClim Laboratory at Tomsk State University for further processing.

Soil samples were collected in the form of columns or with minor gaps in the lower sections of the soil profiles. In the upper horizons, which have been subject to historical ploughing, sampling was conducted from layers 3–7 cm thick, with reference to horizon boundaries. This was deemed necessary in order to facilitate the identification of post-agrogenic processes. This sampling approach is consistent with a recently developed methodology for the differentiated depth-wise sampling of soils to monitor organic carbon content and stocks (Khitrov 2025). The implemented sampling strategy facilitates the detection of post-agrogenic changes in carbon stocks and content, accounting for microtopographic heterogeneity.

In soil profiles Kozh19-1 and Kozh19-2, charcoal fragments were collected from the lower part of the former plough layer. These pieces were suitable for dating. Charcoal was not visually detected elsewhere within the plough layer. Charcoal samples were placed in polyvinyl chloride tubes for transport and subsequent laboratory processing.

Laboratory methods

Air-dried soil samples were analysed in the laboratory following a rigorous protocol that entailed grinding and sieving through a 1 mm mesh. In order to determine the carbon and nitrogen content, it was necessary to remove fine roots and other biogenic residues from the samples under a magnifying glass. Soil colour was measured using a VS450 spectrophotometer (X-Rite, USA). The colour characteristics are presented in the CIE Lab system, a colour space that was proposed by the International Commission on Illumination (CIE) in 1976. CIE Lab is a mathematical model that describes the perception of colour by the human eye. Furthermore, numerical parameters for lightness and chroma on the Munsell scale, a system that is widely utilised in the field of soil science, are provided.

Basic soil properties were determined in accordance with standard analytical protocols. Soil pH was measured potentiometrically in two different solutions: firstly, in distilled water (pHH2O) and secondly, in a 1 M KCl solution (pHKCl). The soil-to-liquid ratio utilised in this study was 1:2.5. The determination of hydrolytic acidity (Ha) was conducted through the utilisation of potentiometric techniques.

The content of organic carbon (Corg) and total nitrogen (TN) in the soil was determined by dry combustion using a Thermo Flash 2000 CN analyser (Thermo Scientific, UK).

The content of exchangeable cations, specifically Ca^{2+} and Mg^{2+}, was determined by displacement with 1M KCl and subsequent atomic absorption spectrometry using a Hitachi-180/60/70. Exchangeable hydrogen and aluminium ions (H^{+}+Al^{3+}) were displaced from the soil with a 1M KCl solution at a soil-to-solution ratio of 1:2.5, followed by potentiometric titration of the filtrate with NaOH to pH 8.2.

The extraction of mobile phosphorus (P_2O_5) and potassium (K_2O) compounds from soil was conducted using a 0.2M HCl solution, with a soil-to-solution ratio of 1:5. Subsequently, the phosphorus content was measured as a blue phosphomolybdenum complex using a photoelectric colorimeter, and the potassium content was measured using a flame photometer.

Loss on ignition (LOI) was obtained for samples exposed at 550°C until weight loss ceased. For the calculation of all mass-based parameters, a correction factor based on the hygroscopic moisture content was used, which was determined by drying the sample at 105°C to constant weight (7 hours).

Particle size distribution was analysed using a laser diffraction particle size analyser LS 13 320 (Beckman Coulter, USA), following sample dispersion with sodium pyrophosphate. Bulk density (BD) was determined subsequent to the drying of the samples to an air-dry state, with this procedure accounting for both the volume of the core sampler and the number of replicates. The carbon and nitrogen stocks were calculated both by soil layer and per 1 m^2 of soil down to a specified depth from the surface. For this calculation, data on carbon and nitrogen concentrations, bulk density, and the thickness of the respective layer were used.

Graphitisation and AMS analysis of three charcoal samples were conducted at the AMS Golden Valley laboratory, employing the unique scientific facility AMS at the Budker Institute of Nuclear Physics, SB RAS (Novosibirsk, Russia). Radiocarbon age calibration was conducted utilising the online version of OxCal 4.4, employing the IntCal20 calibration curve for the Northern Hemisphere (Reimer et al. 2020).

Results

Land-use and Vegetation Development History

Three villages historically existed near the study site. Of these, the oldest, Kozhevnikovo, was founded in 1689 (Kosovets 2012). For the year 1829, the State Archive of Altai Krai (Fond 50) contains two geometric plans of this village's landholdings. The plans coincide geometrically but are executed in different styles. Most likely, one of them, less detailed, is a copy of the other. However, both plans depict arable fields and non-forested lands. Site Kozh19, within which soils were studied, was established in one such landholding. Both plans include a textual legend describing the character of land use and the economy of Kozhevnikovo village.

The Russian State Military-Historical Archive is home to a topographic map that was created circa 1840. Comparing the location of landholdings on this map with that of 1829 reveals that the arable fields had shifted away from the Malaya Chernaya River towards the interfluve, while pine forests expanded along the river. This abandonment of lands closer to the river and movement of arable fields away from it corresponds to the trend noted by the end of the century of replacing winter rye with spring crops. For winter crops, proximity to the river was considered more favourable than for spring crops (Shvetsov and Yukhnev 1900). The location of our site remained as non-forested land (fallow or arable).

Between 1860 and 1865, Makurino village appeared on the site of a former farmstead of the same name, acquiring the northeastern part of Kozhevnikovo village's land. By 1875, Novo-Makurino village emerged, taking over the landholding in which site Kozh19 was later established. As demonstrated in the 1908 plan of Novo-Makurino, site Kozh19 is located in close proximity to the boundary between the village's non-forested and forested allotments.

It is highly probable that the soils were still being utilised for ploughing at this time. However, as in many other areas of the region under study, it is likely that they transitioned to fallow by the 1920s.

The Novo-Makurino village itself persisted into the second half of the 20th century, with some houses visible on CORONA satellite imagery from the 1960s. By 1975, Novo-Makurino village had disappeared according to CORONA imagery. In its final decades, the population of Novo-Makurino specialised in wood processing, a practice that did not support arable farming.

The particulars of 19th-century land administration for settlements within the study region are delineated in Shvetsov and Yukhnev (1900). As demonstrated by the data presented here, soils were ploughed to a depth of up to 18 centimetres, with occasional instances of slightly deeper penetration. The primary tillage implement utilised during the first half of the century was the “rogaluha” sokha (light plough), which was superseded towards the century's conclusion by the Siberian wheeled sokha. The latter effectively turned the soil, thus aiding in weed control. The prevailing agricultural system was characterised by fallow-shifting practices.

Throughout the 19th century, due to a decrease in the area of virgin lands, fallows were increasingly brought back into cultivation. By the close of the century, the average period of fallow land was 15–20 years. The cultivation of these plants, inclusive of periods of fallow, was undertaken over a period of 4 to 10 years.

Based on the ratio of land prepared for ploughing and land sown in 1829, the period of arable use can be estimated at 5 years. At that time, it was noted that the area of exhausted (worn-out) lands amounted to 880 desyatinas (1 desyatina = 1.0925 hectares). Assuming a 5-year period from first ploughing to abandonment and a contemporary area of 36 desyatinas, it would have taken approximately 122 years for 880 desyatinas of exhausted fallow soils to appear. This suggests that such a regime of ploughing must have commenced around 1707, which is close to the founding date of the village, if changes in population over that period are to be considered.

The textual appendix to the 1829 Geometric Plan notes that the population used exhausted soils and young birch forests for haymaking. Shvetsov and Yukhnev (1900) indicate that livestock grazed on fallows in spring and autumn. After grass regrowth, the fallows could be used for haymaking. Therefore, the soils we studied must have repeatedly passed through a grassland ecosystem stage for an extended period before beginning to be overgrown by forest.

The forest stand at the study site Kozh19 exhibits a near-total absence of *Populus tremula*. The age of the oldest and tallest pines ranges from 70 to 92 years. The first canopy layer is dominated by birch and pine, but solitary *Pinus sibirica* and *Picea obovata* also occur. The bark of the pines exhibits evidence of previous fire damage in the form of scarring. The height of these trees is reported to range from 26 to 29 metres.

The branches in the middle and lower sections of the trunks are generally not long, though some trees have long branches on one side. Growth increment analysis demonstrates relative uniformity, with the absence of significant "light-response" increments in the early stages of tree development. It can be inferred that this community formed on the site of a relatively young forest after logging.

Subsequent ground fires, which resulted in the mortality of numerous trees, led to the formation of forest glades. Some of these glades have since been overgrown by trees now approximately 70 years old, while others persist to the present day. This persistence can be attributed to the coenotic stability of nettle-dominated patches, which likely originated as sites where logging residues were accumulated in the past. The forest still contains many stumps of various ages and is subject to selective logging.

In connection with the above, it is difficult to determine the exact age of abandonment of arable land. Archival sources indicate that forests on 25–30-year-old fallows were used for firewood. Several years are also required for tree regeneration to establish on abandoned arable land, especially if livestock grazed on the fallow. Thus, summing the age of the oldest trees (70–92 years), the minimum regeneration period after logging, and the time for trees to colonise the fallow gives an estimated total of about 127 years. This places the plough abandonment around 1892. This timing likely determined the formation of the forest allotment near the study site, as reflected on the 1908 plan. Therefore, we estimate the post-agrogenic period at the study site to be approximately 120–130 years.

Morphology and Classification of Soils, Radiocarbon Age of Charcoals

In all studied profiles, the surface horizon is a mollic humus horizon, and the illuvial horizons were diagnosed as argic. The soil profiles are formed on loess-like clays and exceed 120 cm in thickness. Below this depth, a thick BC horizon with pedofeatures along pores and cracks is present. The studied profiles are presented in Figure 2.

The average Munsell value of the mollic horizon in profile Kozh19-1 within the top 20 cm of dry soil was 3.7 (see Fig. 3). At a depth of 20–50 cm, this value increased to 4.4. The corresponding Munsell chroma ranged from 1.5 to 2.0. In profile Kozh19-2, the Munsell value in the top 20 cm was 4.0, rising to 5.3 at depths between 20 and 50 cm. Chroma varied from 1.6 to 2.4, respectively.

The humus horizon of Kozh19-1 fully meets the colour criteria for mollic horizons according to the WRB 2022. In the Kozh19-2 profile, however, the lower part of the humus horizon does not satisfy the mollic colour criteria, although the value criterion is met for the upper 23 cm. Consequently, a mollic horizon was identified in the Kozh19-2 profile. Field descriptions of profiles 3 and 4 were consistent with the criteria for this horizon.

An argic horizon was identified in all of the profiles studied, as the necessary diagnostic criteria were met. Specifically, clay coatings covering more than 15% of the soil aggregate and pore wall surfaces were present. The upper part of this horizon exhibited an abundance of silt coatings overlaying the clay coatings.

According to the WRB 2022 international soil classification system, the soil profiles studied were classified as Phaeozems (see Table 1). Within Russian classification systems, these soils correspond to seryye (grey) or seryye lesnyye (grey forest) soils.

In all soil profiles, the morphology of the humus horizons bears traces of ploughing. The lower boundary of the plough layer (Ap horizon) varies spatially due to its inherent irregularity and the microtopography of the soil surface.

The greatest thickness of this horizon (22.5 ± 2.1 cm) was recorded in the Kozh19-3 soil profile, which exhibits stagnic properties in the form of Mn-Fe nodules below a depth of 30 cm (see Table 1).

The minimum thickness, 12.3 ± 1.7 cm, was observed in the Kozh19-4 profile. This profile was located in a pine forest with higher canopy closure and a high abundance of fir undergrowth.

The total thickness of the humus profile (A+AE horizons) generally varied in accordance with the thickness of the Ap horizon. The minimum values were also recorded in profile 4.

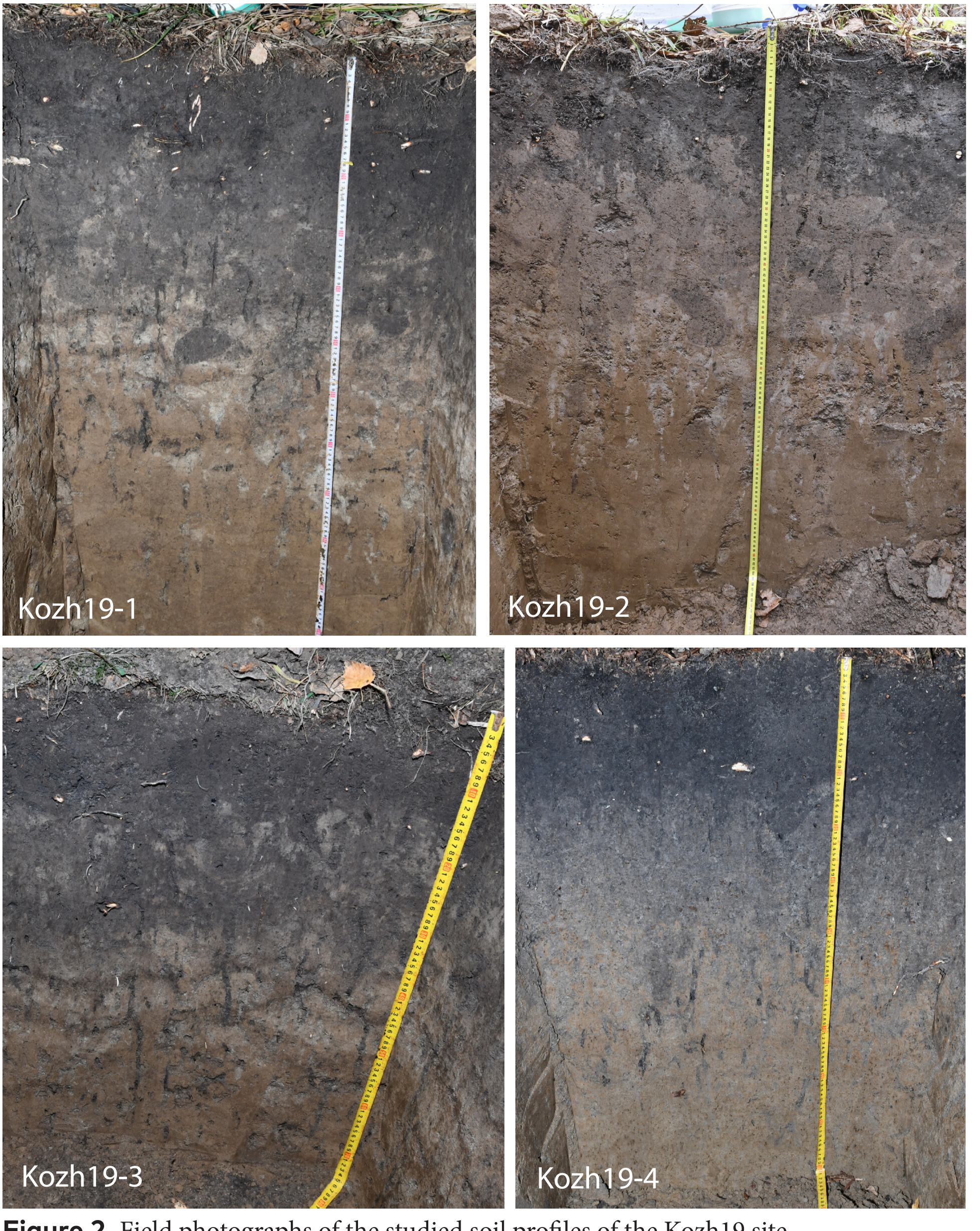

Figure 2. Field photographs of the studied soil profiles of the Kozh19 site.

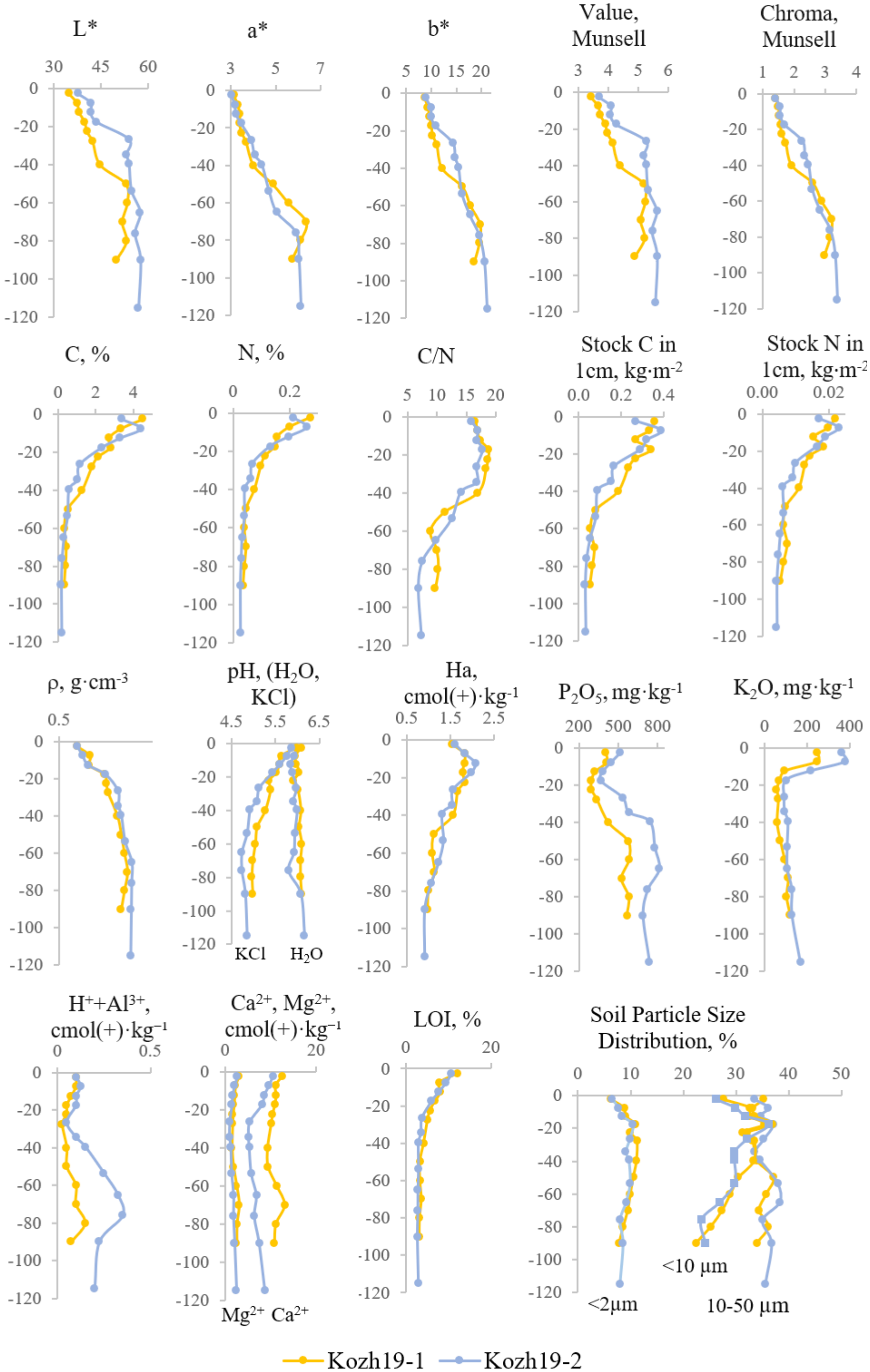

Figure 3. Profile analytical signatures of two soil profiles of the Kozh19 field site.

Table 1. Soil classification (WRB 2022) and profile morphology for the studied sites

Site	Microtopography	WRB classification (2022)	Profile formula	Thickness Ap (Mean ± st. dev.)	Thickness Ap+AE (Mean ± st. dev.)
Kozh19-1	Convex	Luvic Greyzemic Phaeozem (Epiloamic, Endoclayic, Humic)	Ap(0-15/18)–AE(15/20-40/47)–AEBt(40/47-55/65)–EBt(55/65-67/87)–Bt(67/87-120)–BC(120-130+)	18.1±1.8	41.3±5.1
Kozh19-2	Concave, swale	Vermic Luvic Greyzemic Phaeozem (Episiltic, Endoclayic, Aric, Humic)	Ap(0-21/23)–AE(21/23-52/59)–EBt(52/59-68/76)–1Bt(68/76-100)–2Bt(100-125+)	21.9±1.6	54.1±3.6
Kozh19-3	Concave, footslope	Luvic Greyzemic Katostagnic Phaeozem (Epiloamic, Endoclayic, Humic)	Ap(0-21)–AEg(21-49)–AEBt,g(49-70)–Bt,g(70-100+)	22.5±2.1	53.3±2.2
Kozh19-4	Convex	Greyzemic Someric Phaeozem (Epiloamic, Endoclayic, Humic)	Ap(0-12/14)–AE(12/14-36)–EBt(36-50)–Bt(50-75+)	12.3±1.7	35.6±1.1

The humus portion of the soil profile exhibited complex morphology in all soils studied. Beneath the homogeneous humus horizon, which exhibited morphological features inherited from ploughing, a patchy patterned horizon was observed. These patches were grey, light grey or whitish in colour and measured in centimetres or, less frequently, in the first tens of centimetres. Whitish patches attained their greatest areal extent in the Bt horizon. Most of the patches were identified as krotovinas.

In the most well-drained soil profiles located on convex microtopographic sites, dark-brown lamellae were present within the EBt and Bt horizons. Clay illuvial coatings were present within these features at the meso level.

Further insight into the morphology of the former plough layer at Site Kozh19-1 was obtained by analysing three profiles within an open furrow, a ploughed ridge and the adjacent background soil (see Fig. 4).

The original smooth lower boundary of the plough layer (Kozh19-1-2) was best preserved beneath a ridge 12–15 cm thick (Figs 4, 2). This burial resulted in less intensive obliteration processes related to bioturbation.

In the other two profiles, the degree of transformation of the plough boundary was similar. Disturbances were represented by rounded, elongated patches; the largest of these were infilled insect burrows and tunnels created by earthmovers (e.g. rodents).

Figure 5 shows the detailed structure of the profile beneath the ploughed ridge. The left side of the profile reveals the plough boundary in the best state of preservation at the study site, whereas on the right side it is disrupted by a krotovina.

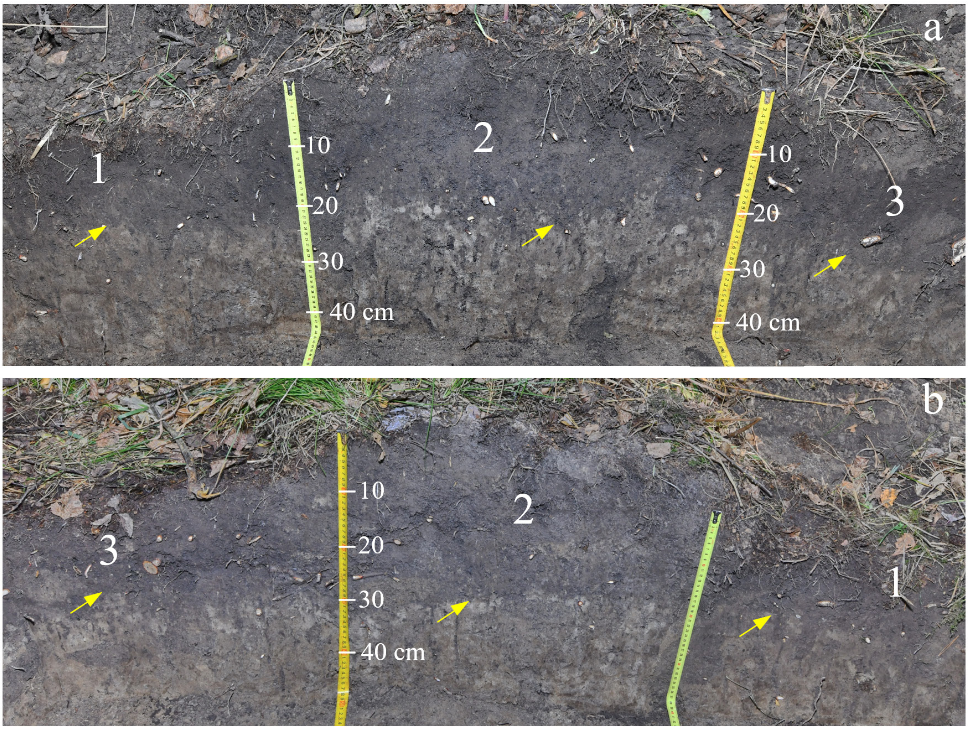

Figure 4. Two trench walls at site Kozh19-1 intersecting open furrows (**1**), ridge (**2**), and adjacent background soil (**3**). Yellow arrows indicate the lower boundary of the residual plow horizon (plow pan).

Carbon stocks, soil chemical properties and radiocarbon age of charcoal

The soils under study were slightly acidic. The lower part of the humus profile in the concavely positioned Kozh19-2 soil was more acidic than in the convexly positioned Kozh19-1 soil (see Fig. 3). The plough layers of the two studied soils had similar average base saturation values of 88.8 ± 1.6% and 85.5 ± 3.0% in Kozh19-1 and Kozh19-2, respectively. Slightly greater differences were evident in the AE horizons of these two soils, with values of 87.3 ± 0.3% and 81.5 ± 1.7%, respectively.

The content of mobile phosphorus forms in the residual plough layers of Kozh19-1 and Kozh19-2 was similar, at 356.9 ± 60 $mg \cdot kg^{-1}$ and 428.0 ± 66.5 $mg \cdot kg^{-1}$, respectively. In the lower part of the humus horizon, however, the disparity increased. While the average value in Kozh19-1 remained almost unchanged at 350.9 ± 66.4 $mg \cdot kg^{-1}$, in Kozh19-2 it increased to 618.2 ± 108.0 $mg \cdot kg^{-1}$. This atypical distribution coincides with the exceptional degree of burrowing by moles (krotovinas) in this profile, a phenomenon not previously recorded to such an extent in soils of the region. This burrowing activity and the associated upward translocation of silty particles also explain the enrichment in mobile potassium.

Figure 5. The former plough layer, buried beneath a ploughed ridge and intersected by a trench at site Kozh19-1. The plough boundary is indicated by a white arrow.

Bulk density in the residual plough layers correlates with the degree of zoogenic transformation. In the residual plough layer of Kozh19-1 it was 0.99 g·cm^{-3}, while in Kozh19-2 it was 0.92 g·cm^{-3}, decreasing in the upper 10 cm to 0.85 g·cm^{-3}. The argic horizon had a higher density in Kozh19-2 (1.67 vs. 1.55 g·cm^{-3}). Higher density values in the argic horizon correspond to better-developed clay coatings.

The distribution of fine earth (physical clay, fraction <2 μm) shows a slight increase in the lower part of the old plough layer compared to the underlying layer. Overall, good particle-size differentiation was noted within the former plough layer, the upper part of which contained almost half the fine earth content of the lower part.

According to the European morpho-functional classification of humus, the soils under study belong to the Terromull form. The carbon distribution across the two profiles shows a stepwise decrease in concentration at the transition from the lower part of the former plough layer to the non-ploughed layer. The upper 5 cm of Kozh19-2 contain less carbon than the underlying layer due to the translocation of material from deeper horizons to the surface via zooturbation.

The carbon stock in the one-metre layer of Kozh19-1 was 15.4 kg·m^{-2}, whereas in Kozh19-2 it was lower at 12.8 kg·m^{-2}. The stocks within the residual plough layers were 6.4 and 6.9 kg·m^{-2}, respectively. The stock in the top 10 cm of soil was 3.5 and 3.3 kg·m^{-2}, respectively.

The distribution of total nitrogen throughout the profile was similar to that of total carbon. In Kozh19-1, the stock was 1.03 kg·m^{-2}, whereas in Kozh19-2 it was lower, at 0.89 kg·m^{-2}, within the 1-metre layer. Within the residual plough layer, however, differences in nitrogen stocks were insignificant.

The results of the AMS dating conducted are presented in Table 2. The difference in the calibrated age of charcoal fragments from the two profiles was approximately 300 years, exceeding the lifespan of the species that formed the forest. Although the confidence intervals overlap, it is highly probable that these charcoals were formed by two different pyrogenic events.

Conversely, within the Kozh19-2 profile, the ages of the two charcoal pieces are similar, and the differences may be associated with the age of the burnt wood. The ages of the dates and their confidence intervals predate the period of land cultivation in the area by a considerable amount.

Table 2. Radiocarbon dating results for charcoal fragments from the Ap horizons. Calibrated ages are given with 2σ errors

Soil profile	Sample	Lab Code	Depth (cm)	14C age (yr BP)	Calibrated 14C age (cal yr BP)			
					mean	from	to	%
Kozh19-1	1	GV-2512	21	983 ± 48	870 ± 55	960	750	95.4
Kozh19-2	1	GV-2513	23	1244 ± 49	1172 ± 67	1284	1063	95.4
Kozh19-2	2	GV-2514	16	1114 ± 52	1028 ± 63	1178	926	95.4

Discussion

Soil morphology and land-use history

Several trends in land use and agricultural practices during the 19th century have been identified in the studied soils for the research area. First, there was a gradual replacement of winter crops with spring crops, manifested in the gradual abandonment of cultivating fields in lowlands and near streams. Spring crops thrived on well-drained slopes and uplands (Shvetsov & Yukhnev 1900).

Secondly, the primitive rogaluha sokha (light plough) was gradually replaced by the more advanced Siberian wheeled sokha (saban), which turned over the soil during ploughing (Shvetsov & Yukhnev 1900). This plough had a wheel and enabled deeper tillage.

Thirdly, as the population grew and new villages emerged, the number of livestock increased, necessitating the establishment of summer pastures (poskotiny) near settlements on the sites of former arable fields. These summer pastures were established on ploughed land with exhausted soils adjacent to villages in the 18th and first half of the 19th centuries. The poskotiny either occupied forests or gradually became overgrown with trees.

These features are reflected in the morphology of the profiles studied. For example, profiles Kozh19-1, 2 and 3, which are located on a slope, were no longer ploughed by the start of the 20th century. Their soils have a plough layer thickness ranging from 18.1 ± 1.8 cm to 22.5 ± 2.1 cm (see Table 1), corresponding to tillage with a wheeled sokha.

The soil profile Kozh19-4 is situated 100 metres away on a levelled surface, at a lower elevation than profiles Kozh19-1 and 2. According to a preserved archival plan from 1908, Kozh19-4 was located at the edge of a forest allotment at that time. This suggests that ploughing at this site had ceased several decades prior to 1908. Its position in a lower-lying area made spring crop cultivation difficult.

The plough layer is 12.3 ± 1.7 cm thick, and its boundary is not discernible in all sections. Together, these factors suggest that this profile was tilled using a rogaluha sokha, which did not produce a uniformly smooth plough pan in all sections.

Due to the thinner humus horizon, the forest community at Kozh19-4 is characterised by greater canopy closure in both the first tree layer and the fir undergrowth. At sites Kozh19-1, 2 and 3, the legacy of a thicker A horizon has resulted in the herbaceous layer dominating, which hinders the regeneration of tree species. When analyzing processes in forest ecosystems, it is necessary to take into account the "historical site factor", since soil characteristics formed as a result of such agriculture can still influence modern biodiversity and tree growth, which has been previously noted in the literature (von Oheimb et al. 2008).

Identified indicators of former ploughing

Morphological analysis of the soil profile structure enabled the identification of the following morphological plough features, formed during the pre-industrial period in the 19th century:

1. A smooth lower boundary of the Ap horizon (Fig. 6), present in all sections when the horizon thickness is 18–22 cm (a legacy of tillage with a wheeled sokha). A smooth Ap horizon boundary is present in some sections only when the Ap thickness is 10–14 cm (a legacy of tillage with a rogaluha sokha).
2. The humic Ap horizon is uniformly coloured. Patches associated with earthmover burrows (e.g. rodent burrows) were formed later and cross the lower boundary of the Ap horizon.
3. The lower boundary of the Ap horizon is accentuated by fragments of charcoal (Fig. 6).
4. Open furrows and ploughed ridges on the soil surface, likely formed during the period of cultivation.
5. The absence of pit-and-mound topography formed by tree uprooting can also be considered a legacy of former ploughing (Bobrovsky 2010). At present, isolated birch windthrows are observed.

6. A stepwise change in the distribution of particle-size fractions upon crossing the lower boundary of the Ap horizon. In Kozh19-1, an accumulation of the silt fraction (10–50 μm) was noted beneath the Ap horizon, which may be a legacy of particle translocation during ploughing (Bobrovsky 2010).
7. The low abundance of aspen (*Populus tremula*) in the forest community confirms the agrarian legacy of the ecosystem under study. In the hemiboreal forest zone, the state of the aspen population provides significant information about prior land use (Loyko et al. 2024).
8. The homogeneous humus horizon has a similar thickness at sites with different microtopography (profiles 1 and 2). There are strong differences in the thickness of the humus horizon at sites with similar microtopography (profiles 1 and 4).
9. Another indirect indicator of ploughing may be the shallower depth of the Bt horizon from the soil surface, which is due to erosion (Yesilonis et al. 2016). In our soils, at the site with convex microtopography, this depth was 41.3 ± 5.1 cm; under concave conditions, it was 54.1 ± 3.6 cm. These differences are caused by a combination of factors, including weaker erosion and more intensive lessivage in depressions.

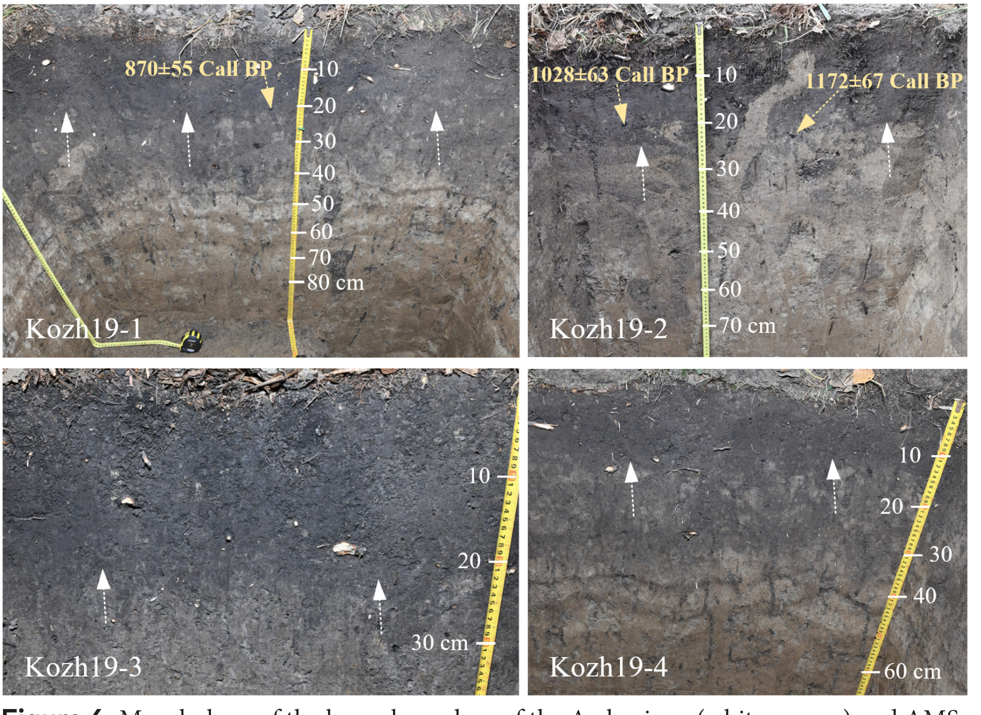

Figure 6. Morphology of the lower boundary of the Ap horizon (white arrows) and AMS-dated age of charcoal fragments.

Taken together, the proposed indicators allow ploughing to be diagnosed in Luvic Greyzemic Phaeozems in the southern part of the forest zone of Siberia, where access to cartographic material is limited.

A distinctive feature of the soils under study is the low quantity of charcoal fragments within the plough layer. Charcoal has repeatedly been used in the past to reconstruct the history of local land use (Bobrovsky et al. 2019; Tomson et al. 2021; Nikodemus et al. 2022). In our study, it effectively indicated the depth of ploughing.

Charcoal fragments from the lower part of the residual plough layer in profiles Kozh19-1 and Kozh19-2 were dated. Initially, it was hypothesised that they might have remained from the stage of clearing the forest plot for initial cultivation. However, the age of the charcoal in the soils we studied was found to be substantially older than the period during which cultivation was possible.

These results are supported by historical data on the agricultural practices specific to the study region. The accumulation of charcoal at the lower boundary of the A horizon was caused by mechanical translocation during ploughing of all the charcoal that had previously accumulated in the original soil horizons.

It was common practice to clear a forest plot in several stages. First, the trees were girdled (ring-barked), after which they were left to dry for several years. The trees were then felled, although the largest ones were often left standing as it was believed that they promoted snow accumulation, which was beneficial for winter crops. The logging residues were gathered into piles, burned and the field was left fallow (Shvetsov & Yukhnev 1900). In the region's fertile soils under sparse herbaceous forests, this tactic was justified due to the lack of need for ash fertilisation and the low effectiveness of fire in the absence of substantial forest litter.

Processes of ploughing legacy disappearance

Post-agrogenic transformation of fallow soils is a complex of processes that includes the degradation of plough layers and the alteration of soil properties towards their zonal analogues (Polyakov et al. 2025). In mineral plough layers under forest cover, the content of carbon and phosphorus often decreases over time (Flinn & Marks 2007).

The rate and direction of these changes depend heavily on the type of soil, the extent of past erosion and the level of soil cultivation. In the first decades, stocks of organic matter increase most rapidly when a layer of plant litter forms on the surface of the mineral soil (Polyakov et al. 2025).

In forests, the prolonged preservation of agrohumic horizons is often observed, frequently alongside the absence of forest litter and a less pronounced albic (podzolic) horizon (Dymov et al. 2023), provided that such a horizon exists in the background soils. Reduced carbon content in soils can persist for centuries, while elevated pH levels, phosphorus content and, sometimes, nitrogen can persist for decades (Orczewska 2009; Brudvig et al. 2013; Bizzari et al. 2015; Kelly & Ray 2023).

Plough layers are one of the most obvious and long-lasting reminders of previous soil cultivation. They remain visible for centuries after the land is abandoned and the forest regrows. Over time, formerly homogeneous plough layers undergo morphological stratification (Kalinina et al. 2015; Telesnina et al. 2016).

After ploughing ceases, lessivage processes occur within the plough layer. This leads to increased contrast in physical clay content (less than 10 μm) between the upper and lower parts of the residual plough layer (see Fig. 3). Similar patterns have been noted previously (Giniyatullin et al. 2015).

The slight increase in particle content directly beneath the plough layer observed in the studied soils can be explained by partilluvation processes, specifically the movement of silt and sand particles from the plough layer into the underlying horizons via the mechanisms proposed by M. V. Bobrovsky (2010).

Another trend is the restoration of soil structure, with a decrease in bulk density and aggregate size. In the profile of the seasonally waterlogged Kozh19-3 soil, Mn-Fe nodules were well-developed, and could have formed either during or after the cultivation stage, as previously noted for fallow soils (Simonova et al. 2021).

The greatest contribution to the disappearance of the ploughing legacy in the studied soils is made by the zoogenic factor, which significantly accelerates the transformation processes of former plough layers in fallow soils (Dayneko and Rusakov 2012). In the Kozh19-2 profile, moles (krotovinas) disturbed the Ap and AE horizons so profoundly that it justified assigning the "Vermic" qualifier to the soil name (Fig. 7). In addition to moles, ants also contribute to zooturbation, especially during the early fallow stages (Mikhaleiko et al. 2023, 2024).

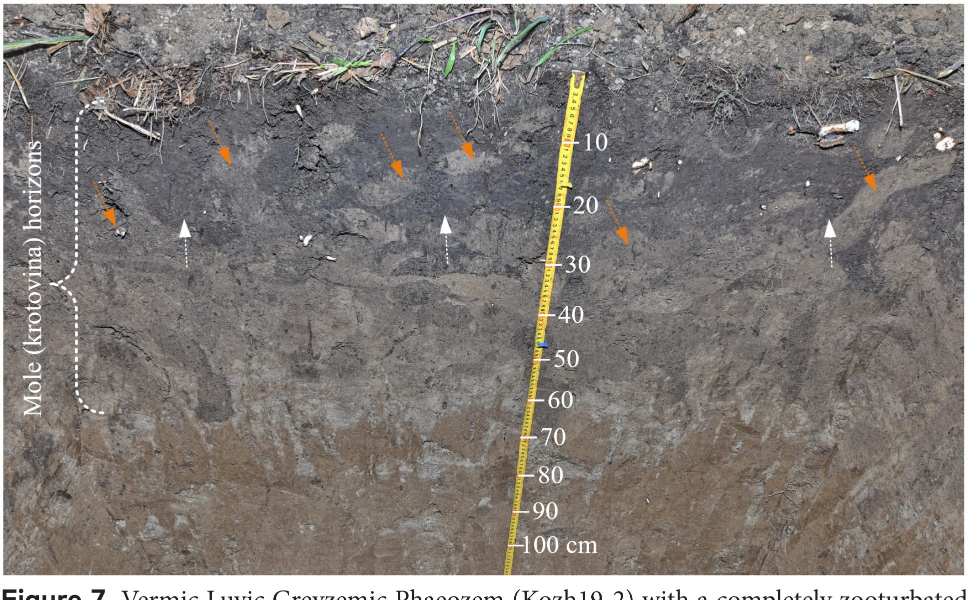

Figure 7. Vermic Luvic Greyzemic Phaeozem (Kozh19-2) with a completely zooturbated AE horizon and numerous crossings of the Ap horizon lower boundary by krotovinas (indicated by orange arrows). The plough boundary is shown with white arrows.

Previous studies have shown that the maximum diversity of litter-dwelling fauna in mixed post-agrogenic forests develops more than 120 years after ploughing, as mixed litter is more favourable for large soil invertebrates than coniferous or deciduous litter alone (Shopina et al. 2023). The forest ecosystem under study also has a mixed stand and undergrowth, resulting in a combination of birch and Scots pine litter, alongside smaller quantities of Siberian spruce, Siberian pine and aspen. Additional moisture promotes the high abundance and activity of moles under these conditions, which may be facilitated by increased earthworm biomass (Shubin 1991).

The morphological features of the studied soil demonstrate that, over the past 120+ years, complete restoration of soil parameters has not occurred. Previous studies have shown that 120 years is insufficient for soil to fully return to its original state (Kalinina et al. 2018, 2019).

Humus profile and carbon stock in fallow soils

In the study region, the deep snow cover protects the soil from severe freezing. This results in high activity of soil mesofauna and herbaceous vegetation susceptible to mineralisation. The absence of a moss-lichen cover on drained loamy hemiboreal soils also contributes to this.

Consequently, there is no distinct litter layer on the surface (Geras'ko 2007; Dyukarev et al. 2022, 2024). On the mineral soil surface, only plant litter from the previous year is present, with significantly less litter from preceding years (mostly woody by then). Forest formation without a litter layer has been studied in the dark coniferous (chern taiga) biome (Abakumov et al. 2020). Consequently, during post-agrogenic succession, carbon and nitrogen stocks only change within the mineral soil horizons.

Soil development proceeded in accordance with plant succession. The appearance of herbaceous vegetation after the plots were abandoned led to the upper part of the A horizon becoming enriched with root-derived carbon. During the transformation of the organoprofile following the cessation of ploughing, the old plough layer becomes differentiated in terms of carbon content, with an increase in this parameter in the upper third (0–10 cm). This is associated with turf transformation in the early stages and leaf litter input in the later stages (Kurganova et al. 2022).

In Siberia, changes in carbon content following soil cultivation can vary in direction. However, a decrease is more common, particularly in forest-steppe and steppe soils (Bobrenko et al. 2021; Nechaeva & Smolentseva 2024).

In the southern part of the forest zone, an increase in carbon content in the upper part of the humus horizon is more frequently observed (Bulysheva et al. 2021). In the taiga, especially near ancient settlements, the impact of agriculture leads to an increase in carbon content and stocks in mineral soil horizons (Derbilova et al. 2024). Seasonal fluctuations in soil organic carbon content have also been observed over time in the plough layers of autonomous soils (Dłuzewski et al. 2019).

The carbon stocks of the studied profiles fall within the ranges reported in the literature for the same type of soil (Azarenko et al. 2023; Dyukarev et al. 2024).

The distribution of carbon concentrations in the studied soils indicates a predominance of surface-derived inputs, as well as a gradual transformation of the A horizon into a background A horizon characterised by a maximum in surficial carbon content.

An increase in carbon stock towards the upper half of the plough layer indicates carbon accumulation within the former plough horizon (Khitrov 2025). Despite increased microbial and enzymatic activity, an increase in the carbon stock of the upper 10 cm of fallow soils can occur (Samokhina et al. 2025).

In the case of the Kozh19-2 profile, the high mole activity somewhat distorts this pattern due to the upward translocation of less humified material to the soil surface. Comparing the carbon stocks in the 20–50 cm depth range of the two studied profiles shows that they are greater in Kozh19-2, as is the clay particle content. This is related to the profile's intense zooturbation. Under conditions of forest-derived surficial carbon input, zooturbation activity will further contribute to an increase in carbon stocks.

Conclusions

This study focused on the soils of secondary forests in the southern forest zone of Western Siberia. The study sites were located on former 19th-century arable land, as identified on historical maps. The research identified and categorised morphological and chemical indicators of historical ploughing that remain in the soil 120–130 years after agricultural use ceased.

The key diagnostic features of former ploughing in the studied Luvic Greyzemic Phaeozem soils are: a smooth lower boundary of the Ap horizon; uniform colouring; charcoal fragments along the lower boundary of the Ap horizon; open furrows; an absence of the characteristic topography of forest pit-and-mounds formed by tree uprooting; a stepwise change in particle size distribution at the Ap horizon boundary; low aspen abundance in the tree stand; and specific spatial variations in horizon thickness (different Ap thickness at sites with similar microtopography and similar Ap thickness at sites with different microtopography).

The investigation also demonstrated that the disappearance of ploughing features is largely driven by zoogenic activity (e.g. moles, ants, insects and earthworms), which transforms the original morphological patterns. Despite the lengthy recovery period, soil characteristics have not returned completely to a conditionally background state within 120 years.

Post-agrogenic dynamics in the studied soils are characterised by the accumulation of organic carbon in the upper part of the former plough layer, which is associated with the input of plant litter and root material during natural succession. At the same time, total carbon stocks within the one-metre soil layer remain significant.

This work is one of the first attempts to systematically identify indicators of historical ploughing in the soils of southern Western Siberia. The proposed set of diagnostic features can be used to identify ancient arable land within the region's forest landscapes, particularly when precise cartographic sources are unavailable. The results obtained contribute to our understanding of the long-term ecological legacy of traditional agriculture and of the processes involved in ecosystem recovery when land use is abandoned.

Acknowledgements

Some of the samples were dated using a unique scientific facility, the Accelerator Mass Spectrometer, G.I. Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences.

This work was supported by the Russian Science Foundation (project number 24-27-00417).

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