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RESEARCH ARTICLE

An unploughed reference pedon of Luvic Greyzemic Phaeozem under an old-growth forest in the long-cultivated North Pritom'e region in south-east Western Siberia

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Abstract

This study presents a morphological and analytical characterisation of a native reference soil developed under a old-growth, non-agrogenic tall herb aspen forest in the south-eastern part of Western Siberia's forest zone. The main objective was to establish a baseline description of a Luvic Greyzemic Phaeozem, the vast majority of whose analogues in the region have been converted to arable land. Conducted at the 'Ust-Sosnovka' key site, the research employed detailed profile descriptions, morphometric analyses and a range of laboratory methods, including carbon elemental analysis, carbonate determination and sub-micromorphological investigations of carbonate pedofeatures. The results revealed a thick, well-structured and highly biogenic soil profile, characterised by a pronounced accumulative distribution of organic carbon (C_(org) reaching 5.2–9.9% in the 0–10 cm layer) and low bulk density (0.6–0.7 g/cm^3), which is indicative of intense bioturbation. A significant stock of inorganic carbon (Cinorg) was identified in the middle and lower horizons, with neoformations showing signs of active dissolution and leaching under the humid climate. The soil is classified as prograding, with no signs of degradation or relic features. The calculated carbon stocks emphasise the importance of both the surface and deep horizons in the total carbon budget. The characterised pedon serves as a crucial reference for quantifying the direction and magnitude of centennial-scale agrogenic transformation in analogous soils. The findings emphasise the importance of conserving such native ecosystems for monitoring carbon stocks and assessing the sustainability of land management. Consequently, this soil should be included in regional soil protection registries, such as a prospective Red Book of Soils for the Kuzbass region.

Keywords
Reference soil, soil organic carbon, inorganic carbon, carbon stocks, soil morphology, old-growth forest

Introduction

Over recent centuries, the boreal belt of Europe and Asia has experienced extensive transformations of its natural environment, largely associated with the complete abandonment of traditional agricultural practices, particularly the slash-and-burn cultivation system (Henttonen et al. 2020; Tikkanen and Chernyakova 2014). The most substantial change in land use systems in Eurasia during the 20th century occurred in Russia (Henebry 2009; Lyuri et al. 2010), where almost 650,000 km^2 of agricultural land was abandoned over the course of a century (Lyuri et al. 2010). By 2020, the area of permanent arable land in Russia had stabilised (Rukhovich et al. 2025).

A wide spectrum of post-agrogenic ecosystems is now developing across vast expanses of the south of the forest zone (Ryzhova et al. 2020; Smirnova et al. 2017; Telesina and Zhukov 2019). Former agricultural land that is currently being reforested plays a significant role as a carbon sink (Poeplau et al. 2011; Post and Kwon 2000; Kurganova et al. 2021). Studies have shown that the influence of climate change and land use change on the carbon balance is comparable (Rolinski et al., 2021). This makes retrospective regional landscape studies pertinent in order to understand the extent to which prior land use has displaced them from equilibrium.

In the context of contemporary climate initiatives, such as carbon neutrality and the '4 per 1000' initiative, it is crucial to conduct regional assessments of the impact of historical and current land use on soil organic carbon (SOC) stocks. Effective management of SOC stocks through land use management requires an in-depth understanding of how contemporary organic matter stocks have formed under various natural and geographical conditions (Minasny et al. 2017). Studies at global and regional levels demonstrate the complex and ambiguous dynamics of SOC stocks in both arable and abandoned land, which are heavily dependent on initial soil types, climates, farming systems, the duration of restorative succession and local conditions (Zomer et al. 2017; Chenu et al. 2019).

Methods such as soil resampling studies, long-term experiments and the space-for-time substitution approach are frequently employed to assess changes in soil organic carbon (SOC) stocks over time (Smith et al. 2020; Chendev et al. 2022). Refining temporal models of SOC stock changes across different farming systems often involves comparing reference soils in native ecosystems with arable soils (Bruun et al. 2015; Xiao et al. 2024). Analysis of native soils may also be necessary for practical purposes, such as assessing soil fertility for cultivation (Kayugina & Eremin 2022).

Evaluating the agrogenic evolution of soils often requires referencing background, non-ploughed soils (Chendev et al. 2022; Trubnikov & Kryuchkov 2024). Consequently, researchers often struggle to locate native, unploughed natural soils in regions with extensive agricultural land. Such soils can be identified using historical cartographic materials that prove the absence of past agricultural impacts (Smirnova et al. 2025).

The prospect of achieving carbon neutrality in Russian agriculture is challenging, requiring significant changes to many agricultural processes (Ryabov et al. 2024). However, the recent discovery of a soil self-restoration process under continuous ploughing (Zhidkin et al. 2024) offers a fresh outlook on the carbon neutrality of modern arable lands. It is possible that on long-established arable land, processes of carbon loss may cease, negating the need to convert these lands to fallow. However, an expanded understanding of the processes that will occur on newly reintroduced fallow lands is also required. Russia is currently witnessing the conversion of fallow land back into arable use (Nechaeva 2023). Research into the degree of soil transformation under continuous cultivation over long time periods and across a wide range of geographical conditions could provide answers to these questions.

The southern part of the forest zone in Western Siberia is one region with a large area of fallow land. There is still a lack of studies in this region that use a historical-ecological approach and modern analytical methods, such as dry combustion using elemental analysers, to quantitatively assess the extent to which carbon stocks differ in genotypically similar soils with different agrogenic histories measured over centuries (Loiko et al. 2025). This study investigated a reference native soil, similar soils of which have almost entirely been converted to arable land. According to the WRB 2022 classification (IUSS 2022), the soil in question was identified as a Luvic Greyzemic Phaeozem. According to the 2004 Russian classification (Shishov et al. 2004), it was categorised as dark grey super-deeply bleached soil (temno-seraya sverkhglubokoosvetlennaya). The absence of agrogenic impact on this soil over hundreds of years has previously been substantiated (Loyko et al. 2024). This paper presents a morpho-analytical characterisation of these reference native soils. In future, this soil area can be used to evaluate the agrogenic transformation of soils over a century-scale timeframe under the conditions of the southern taiga (podtaiga) in south-eastern Western Siberia.

Materials and methods

The research was conducted at the key study site, 'Ust-Sosnovka' (56°5'52" N, 84°59'25" E), which is located in the Kemerovo region (Kuzbass). This site was previously described in detail in our work (Loyko et al. 2024) (see Fig. 1). Five soil profiles were studied within an old-growth forest ecosystem characterised by a broad-herb aspen forest. According to cartographic sources, this forest has not been cleared for agricultural use for over 230 years. Given the sparse population in the region prior to this period and the lack of nearby settlements, this forest can be categorised as non-agrogenic. However, it should be noted that the absence of agricultural use does not preclude selective logging within the forest.

The study site is characterised by subdued, hummocky-depression microrelief. The area generally slopes downwards from the interfluve towards the Tom River. The interfluve's edges are drained by a network of gullies and ravines. Soil profiles were examined on the summits of flat-topped microtopographical hummocks (micro-watersheds). Vertical height variations are on the order of metres, while these flat-topped hummocks extend horizontally over tens of metres. Under these conditions, the influence of erosional processes is minimised.

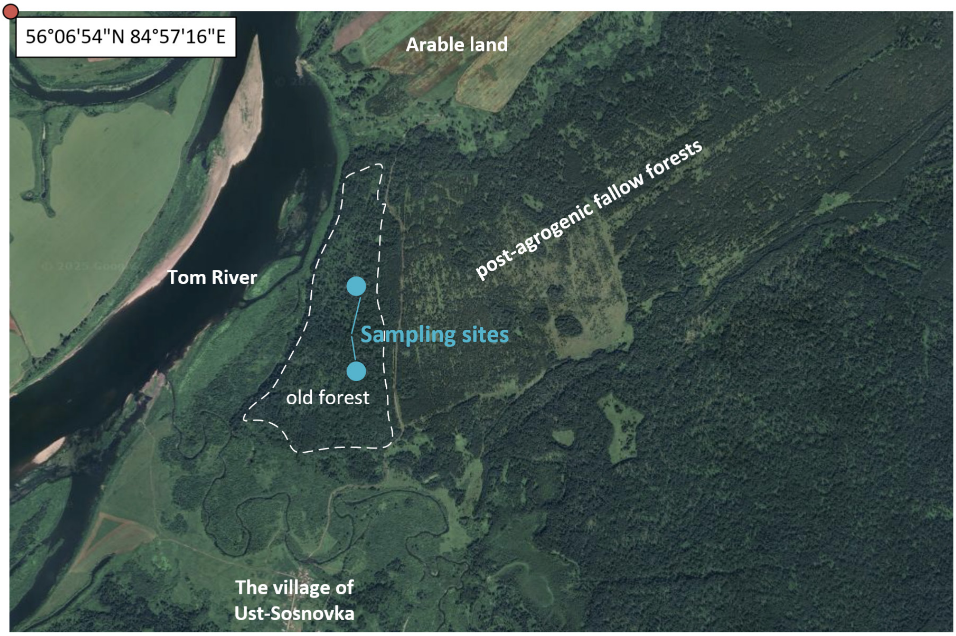

Figure 1. The study area and sampling sites.

Samples were collected from each soil pit down to a depth of 35 (40) cm at 5 cm intervals, followed by 10 cm intervals. At the transition from the AE horizon (AUel in the Russian classification system) to the Bt horizon (BT in the Russian classification system), sampling was sometimes conducted at five cm intervals if the boundary was distinct. In other instances, a 10 cm interval was maintained. Continuous core sampling was performed down to a depth of one metre. Below this depth, sampling was selective. From 120–140 cm down to the underlying sand layer at 210–240 cm, samples were collected using an Eijkelkamp auger. In total, 114 samples were collected. Sampling below two metres was undertaken to account for inorganic carbon compounds.

Bulk density samples were collected in duplicate from all soil profiles using the cutting ring method. To determine bulk density at depths greater than 130–140 cm, a special auger was driven up to 50 cm from the bottom of the pit; below this point, bulk density was assumed to be the same as the last measured sample. A total of 67 bulk density samples (in duplicate) were obtained.

The total carbon content (Ctot) and soil organic carbon (Corg) in the collected samples were determined using a Thermo Flash 2000 CN-modification elemental analyser. The carbonate (Cinorg) content was determined using the alkalimetric method (according to Kozlovsky). Non-silicate forms of Fe (Fe_2O_3_ox) and Al (Al_2O_3) were measured using Tamm's method. In four of the profiles, the Mehra-Jackson method was also used to determine Fe_2O_3_d. The mass fraction of exchangeable calcium (Exch. Ca) and magnesium (Exch. Mg) ions was determined by inductively coupled plasma atomic emission spectrometry. Hydrolytic acidity (Ha) was determined according to the Kappen method. The mass fraction of phosphorus (V) oxide (P2O5 lab) present in mobile compounds was determined by the Kirsanov method. The mass fraction of potassium oxide (K2O lab) present in mobile compounds was also determined by the Kirsanov method. Soil colour was determined using an X-Rite VS450 spectrophotometer. Particle size distribution was determined using the pipette method.

Due to the lack of data on the morphology of carbonate neoformations, and given the importance of this carbon pool, investigations of the carbonate horizons were conducted at meso- and submicro-morphological levels.

Results and discussion

The old-growth forest ecosystem under study is represented by a tall aspen forest (Fig. 2). This forest tract exhibits features characteristic of old-growth woodlands (Bobrovsky 2010). The examined ecosystem's structure displays all indicators of a prolonged forest history: an uneven-aged aspen stand; a gap-phase mosaic associated with groups of dead aspen trees; a clustered arrangement of various species of shrub; tall herb species growing within the gaps; windthrow pits and mounds of different ages alongside coarse woody debris; aspen populations with different biomorphs; a distinct synusial structure to the herb layer under the aspen canopy including synusiae of spring ephemeroids; a high frequency of peonies (*Paeonia anomala*); and numerous synusiae of common hop.

The canopy cover of the studied forest is approximately 0.6–0.7. The stand composition formula is 9 aspen : 1 birch. The understorey features clustered growth of rowan, bird cherry, honeysuckle, guelder rose, and hawthorn. Hop frequently grows as a vine on the shrubs. In canopy gaps, the herb layer reaches a height of 1.5–2 m, while under the canopy it is 70–80 cm tall. The herbaceous layer is dominated by *Aconitum septentrionale*, *Paeonia anomala*, *Delphinium elatum*, *Crepis sibirica*, *Heracleum dissectum*, *Parasenecio hastatus*, *Cirsium heterophyllum*, *Milium effusum*, *Aegopodium podagraria*, *Pteridium aquilinum*, and *Urtica dioica*. Mosses are distributed in patches on coarse woody debris, with a cover not exceeding 5%. In May, the main flowering species are spring ephemeroids with a projective cover of 10–20%, including *Erythronium sibiricum*, *Pulmonaria obscura*, *Ranunculus auricomus*, *Anemone caerulea*, *Anemone sylvestris*, and *Corydalis bracteata*.

Figure 2. Old aspen tallgrass forest.

Such tall herb forests in the study region are typically characteristic of either more humid locations (lower parts of the slopes) or taiga areas located dozens of kilometres away from the Tom River (Loiko et al. 2015). A common feature for all tall herb forests in the region is the absence of a continuous forest litter layer. The turnover of herbaceous and woody litter is rapid, measured in just a few years (Abakumov et al. 2020; Dyukarev et al. 2022, 2024).

The primary peculiarity of the identified forest is the nearly complete dominance of aspen in the stand, despite its location on one of the best-drained upland (plakor) positions. All literature sources describing such well-drained uplands in the Tom River region and the Kuznetsk Basin with dark grey soils (Luvic Greyzemic Phaeozems) mention *Calamagrostio arundinaceae–Betuletum pendulae* associations (Ermakov 2003), or birch forests with *Calamagrostis* and *Brachypodium* (Lapshina 1963). The summary of vegetation for the Kemerovo Oblast, specifically the Insk-Tom forest-steppe district to which this forest belongs, states that no closed forest stands occur in areas of dark grey soils and degraded chernozems: woodlands have a park-like appearance and "clumps of birch with aspen in depressions" are more common among open spaces (Kuminova 1949). Dense forest stands composed of large trees are found in the immediate vicinity of villages, preserved as "protected oak groves". It is likely that our forest tract belonged to this category of land.

This atypical vegetation, which is uncommon for a Luvic Greyzemic Phaeozem, formed due to the forest's long-term development without conversion to agricultural land. This plant community shows what the potential vegetation could be if the area were not managed by humans. Therefore, this soil is representative of native soils in the elevated interfluves at the boundary between the southern taiga (podtaiga) and the northern forest-steppe in south-eastern Western Siberia.

Let us now briefly consider the morphological features of the studied pedons. Horizon designations follow the Russian Soil Classification (Shishov et al. 2004). The description is provided for Profile 4 (Fig. 3).

Horizon AU (0–28 cm). Dark grey in colour, with a medium loamy texture and granular-crumb structure. Loose consistency, abundant living roots (d=2 cm). Nearly all aggregates are earthworm casts. Several centimetres-sized charcoal fragments were encountered. There is a gradual transition to the underlying horizon.

Horizon AUel,b (28–36/40 cm). It is dark grey with coatings of brownish material and thin, whitish films of silt-sized, washed grains. Medium loam. Granular-crumb structure. Slightly compacted with a wavy boundary and a distinct transition.

Figure 3. Example of studied soil profiles of Luvic Greyzemic Phaeozem.

Horizon AU/BELgl (36/40–52/57 cm). Dark grey with brownish mottles and whitish fragments of washed-out silica. Numerous root channels, and earthworm and insect burrows filled with dark grey material. Medium loam. Nutty structure. Presence of brownish-brown silty lamellae. Dark grey molehills. Compacted. Shallow pocket-like boundary, distinct transition.

Horizon BTa,gl,el (52/57–60/73 cm). Light brown with dark grey mottles and whitish silt coatings. Heavy loam. Nutty-prismatic structure. Dense, with layers of coarse lamellae. Brownish-brown clay coatings along cracks and large pores. Tonguing boundary, clear transition.

Horizon BTa,gl (60/73–90 cm). Light brown with humus coatings, coarse nutty-prismatic structure, heavy loam, with large silty lamellae. Brownish-brown clay coatings along cracks and large pores. Dense, wavy boundary with a gradual transition.

Horizon BTgl (90–119/129 cm). Light brown background with thin, brownish lamellae. Heavy loam, blocky-prismatic structure, dense. Brownish-dark brown clay coatings along cracks and large pores. Wavy boundary with an abrupt transition.

Horizon BCCa (119/129–144 cm). Pale light brown, heavy loam, blocky, compacted, finely porous. It effervesces with hydrochloric acid. Carbonates are present as thin veinlets. There are clay coatings along cracks and large pores, with a smooth boundary and clear transition.

Horizon ICa (144–170+ cm). Yellowish-pale, dense, structureless, heavy loam with fine porosity. It shows vigorous effervescence with hydrochloric acid. Loess-like loam.

Morphometric parameters were calculated for the five soil profiles studied. The AU horizon was 19.4 ± 6.2 cm thick (mean values and standard deviations are provided throughout). The AU horizon with heterogeneous colouration due to local bleaching or brownish speckles had a thickness of 39.2 ± 6.8 cm. The thickness of the range with well-expressed bleaching (Greyzemic) features within the humus horizon was 26.3 ± 7.6 cm. The thickness of the argic horizon with lamellae was 80.4 ± 10.3 cm. The depth of effervescence with hydrochloric acid was 122.9 ± 8.9 cm. The total thickness of clay cutans (argillans) was 30.6 ± 14.3 cm. The lower boundary of continuous humus impregnation of the soil mass was found to be 66.1 ± 34.4 cm. The lower depth of the occurrence of humus morphons was 76.5 ± 17.4 cm. The thickness of the transitional horizon between the humus and argic horizons, which exhibited bleached spots, was 14.6 ± 2.5 cm.

Thus, this soil, which has developed on loess-like loam, has a thick, highly biogenic and well-developed profile. Earthworm channels are present in horizontal sections down to a depth of 1 m. On a horizontal section made at 60 cm depth, the cross-sectional area of earthworm burrows constitutes the first few percent of the total section area.

The subhorizons within the humus horizons of the reference soil have smooth, gradual transitions; sharp boundaries are absent until the appearance of the horizon with lamellae. The soils have a Terromull humus form (Zanella et al. 2011).

Figure 4 shows the results of soil colour determination at different depths using the CIE L*a*b* system. The lightness (L*) of the uppermost part of the humus horizon ranges from 2.8 to 4, corresponding to the AU (dark humus) horizon in the Russian classification. The horizon thickness is up to 50 cm. There are also no signs of a variegated AEL horizon with light-whitish morphons. Therefore, according to the Russian classification, the soil is classified as dark grey soil and not grey soil, for which whitish spots are characteristic within the depth range of 20–50 cm.

The humus horizon gradually lightens with depth in the soil profile. No darker horizon is distinguished at the boundary between the A and Bt horizons. This indicates an absence of relic features and degradation in this soil. It is known that dark-humus soils undergoing degradation and transformation into podzolic soils possess a second relic humus horizon (Alexandrovskiy et al. 2022).

Using the recently developed methodology to interpret the distribution of carbon in humus horizons (Khitrov 2025), alongside the colour pattern, suggests that this soil is undergoing humic progradation. The uppermost horizons are the darkest in the profile and contain the highest concentration of organic carbon. This indicates that the soil is developing towards a darker, more humus-rich state as organic matter moves downwards through pedoturbation, which is consistent with the model of surface material translocation in forest soils proposed by Bobrovsky (2010).

The other two colour coordinates, a* and b*, increase as total carbon content decreases down the profile. The a* coordinate, which is responsible for the red pigment, reflects the degree of expression of illuviation features, or conversely the accumulation of whitish silt coatings, in the argic horizon. For example, the highest values of standard deviation are observed at a depth of 65 cm, which is related to the formation of both brownish clay illuviation features and brownish-whitish morphons at this depth (Fig. 4). The peak in the a* pigment indicates that illuviation features are most developed within the 60–110 cm depth range. The downward shift of the b* peak relative to the a* peak indicates a decrease in organic matter enrichment of colloids migrating to this depth.

In the soils that we studied, carbonate pedofeatures were predominantly found in association with pore spaces and their immediate surroundings (see Figure 5). In forest soils, carbonate pedofeatures in the upper carbonate horizons are weakly expressed due to the dissolution and leaching of carbonates by downward water movement. Collomorphic accumulations are mainly present, but semi-destroyed crystallomorphic films can also be found. We observe coatings of carbonates on the plasma of clay-humus cutans and iron-stained, finely dispersed films. In the lower horizons, well-formed calcite crystals and pseudomycelium along pore spaces are present (Figure 5c, d).

Examining the submicro-morphological structure (Figure 6) reveals a large number of acicular carbonate pedofeatures in forest soils. This indicates that the colloidal solution is frequently saturated or supersaturated with calcium salts. These relatively young neoformation features arise from either the downward migration of solutions or the redistribution of litogenic carbonates (Golubtsov 2017; Bulysheva et al. 2021). Various forms of calcite crystals are present, including large and small acicular, rod-shaped and flaky crystals, which occur both as separate masses and on the surface of a fairly dense collomorphic or crystallomorphic film within pores.

In addition to forest carbonate pedofeatures, inherited arid granular forms of carbonate neoformations are observed (see Figure 6b). These carbonate grains exhibit etching cavities. In the studied soils, under humid climatic conditions and a weakly leaching water regime, waters saturated with carbonic acid penetrate downwards, leading to grain etching. Following evaporation and supersaturation with respect to calcite, redeposited calcium forms acicular calcite. Such neoformation forms are well preserved due to their association with dead-end pores. This is evidenced by the fact that such granular forms are not spatially associated with clay coatings. Thus, in natural forest soils, a predominant process of dissolution and leaching of carbonates is underway.

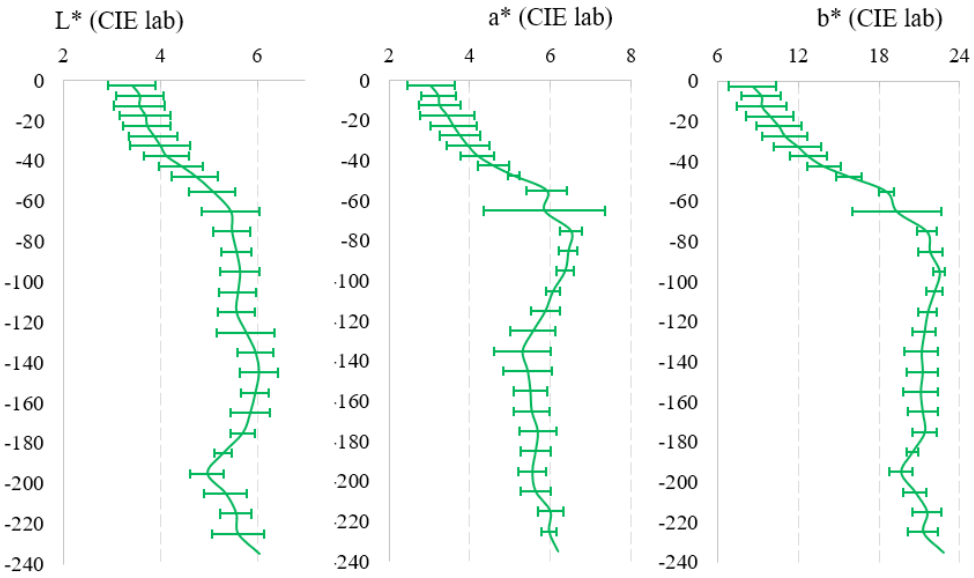

Figure 4. The color of the horizons of the reference pedon Luvic Greyzemic Phaeozem is presented as mean values and standard deviations of color coordinates in CIE Lab space (n = 5).

It should be noted that the profiles studied were located in areas with the smallest catchment sizes, which represented the highest points of the microtopography. When moving downslope, the carbonate horizons quickly extend beyond the soil profile. In the studied landscape, carbonates are unstable and tend to be lost from elevated positions.

Figure 7 shows the mean values and standard deviations for all the analytical characteristics studied. The Corg of the investigated soils exhibits an accumulative distribution pattern. In the top 0–10 cm layer, its content reaches maximum values ranging from 5.2% to 9.9%. Cinorg shows significantly greater variability and exhibits a cumulative peak at a depth of 150 cm, likely corresponding to the depth at which the wetting front most frequently descends. A layer of non-effervescing sand begins at a depth of 230 cm. The contents of exchangeable calcium and magnesium follow a similar trend of surface accumulation. Mobile forms of phosphorus and potassium are distributed similarly, except phosphorus content increases again in the lower horizons.

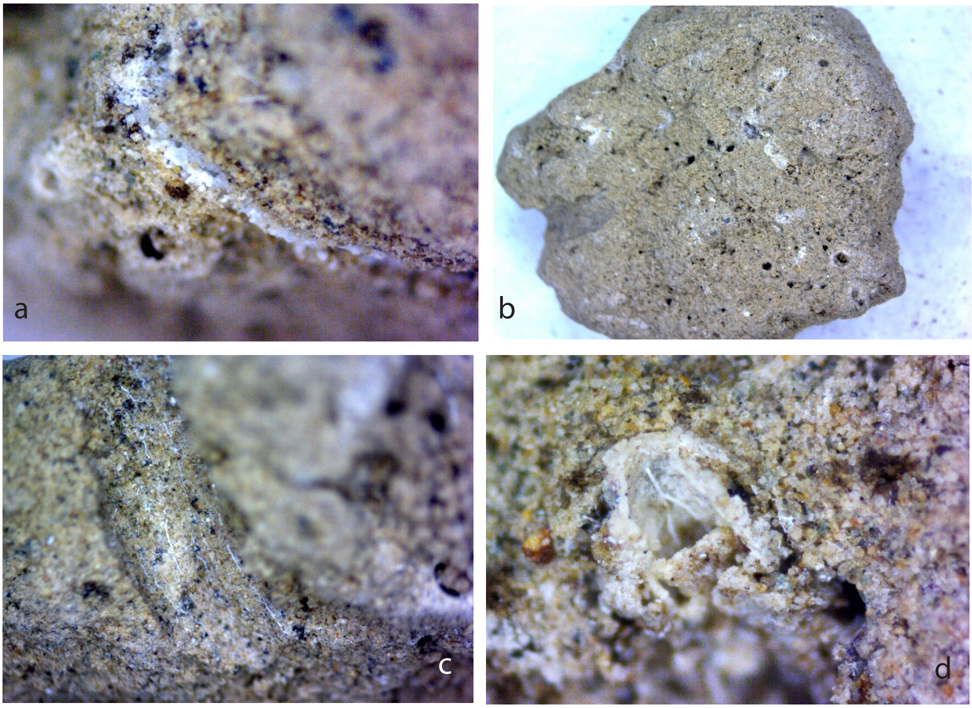

Figure 5. Mesomorphological structure of carbonate horizons of profile US22-4. **a** – Large calcite crystals, horizon Ica (150-160 cm). **b** – Close-up of carbonate ped, horizon BCCa (128-138). **c**, **d** – Carbonate film in pores with well-defined white veins of pseudomycelium, horizon ICa(150-160).

In the tall herb aspen forest, it (bulk density) is 0.6–0.7 g/cm^3, which is the minimum possible value for Luvic Greyzemic Phaeozems and reflects the high activity of soil meso- and macrofauna. This low density, combined with the good availability of phosphorus and potassium in the soil, ensures soil fertility and contributes to the giant size of herbaceous plants.

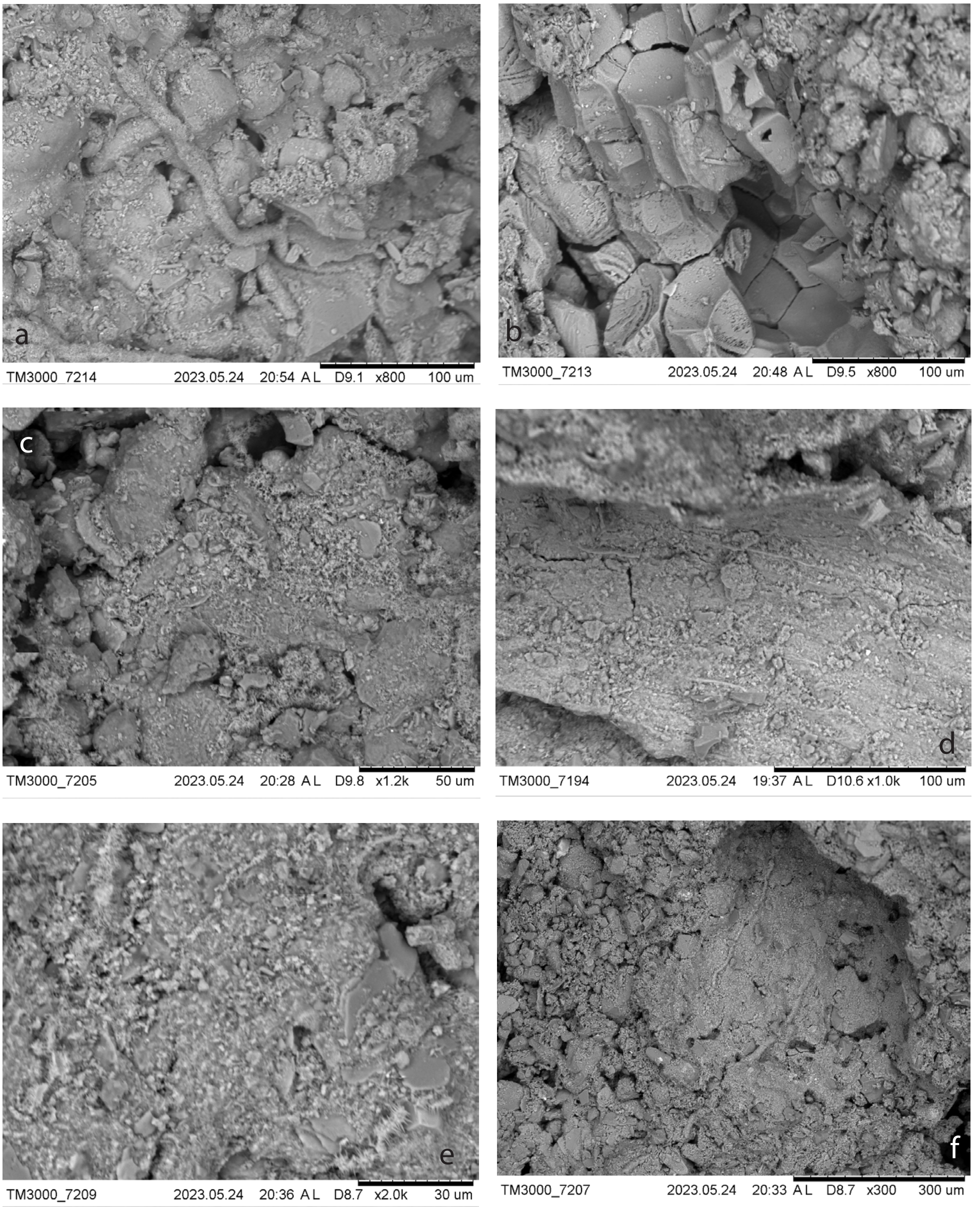

Figure 6. Submicromorphological structure of soil calcite in the carbonate horizon US22-4. **a** – Rod-shaped carbonates, horizon ICa(150-160). **b** – Large calcite crystals, horizon ICa(150-160). **c** – Coating of soil mass with needle-shaped accumulation of calcite, horizon ICa(150-160). **d** – Carbonate crust of colloform structure with cracks and needle-shaped, rod-shaped and flocculent carbonate units on the surface, horizon BCCa(128-138); **e** – Accumulation of needle-shaped calcite, horizon ICa(150-160); **f** – The pore is covered with a crystallomorphic film, with needle-like and rod-shaped contractions on the surface, horizon ICa(150-160).

The analytical characteristics of the reference pedon Luvic Greyzemic Phaeozem were obtained by averaging data from five individual profiles. The humus horizon is defined as slightly acidic (pHwater 5.1); below this, the reaction becomes moderately acidic (pHwater 4.6–5.0). In the lower part of the dark grey forest soil profiles considered, the level of acidity is determined by the depth of the carbonate horizon. At the upper boundary of the carbonate layer (120 cm), the pHwater value for all the studied profiles is neutral (pHwater 6.5), and below this level, the reaction is alkaline (pHwater 7.5). The degree of variation in hydrolytic acidity ranges from 2 to 7 cmol(+) per kg of soil.

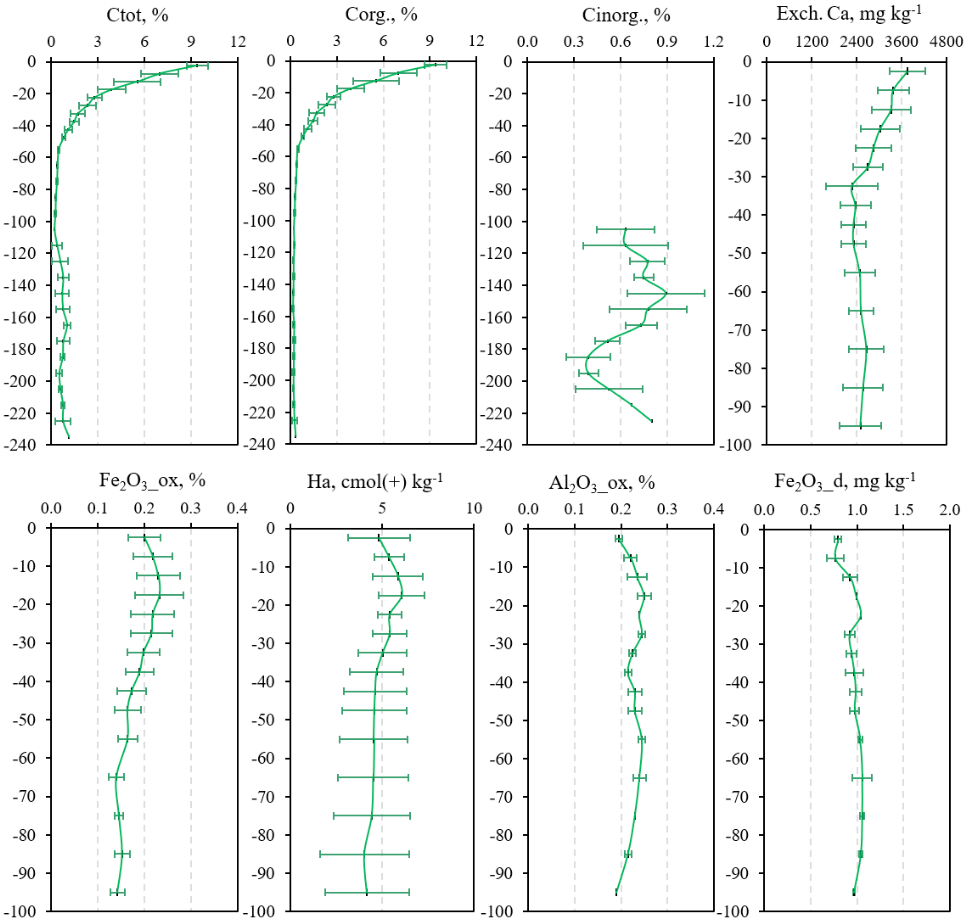

Figure 7. Profile analytical characteristics of the reference pedon Luvic Greyzemic Phaeozem obtained by averaging data from five individual profiles. Standard deviations are shown.

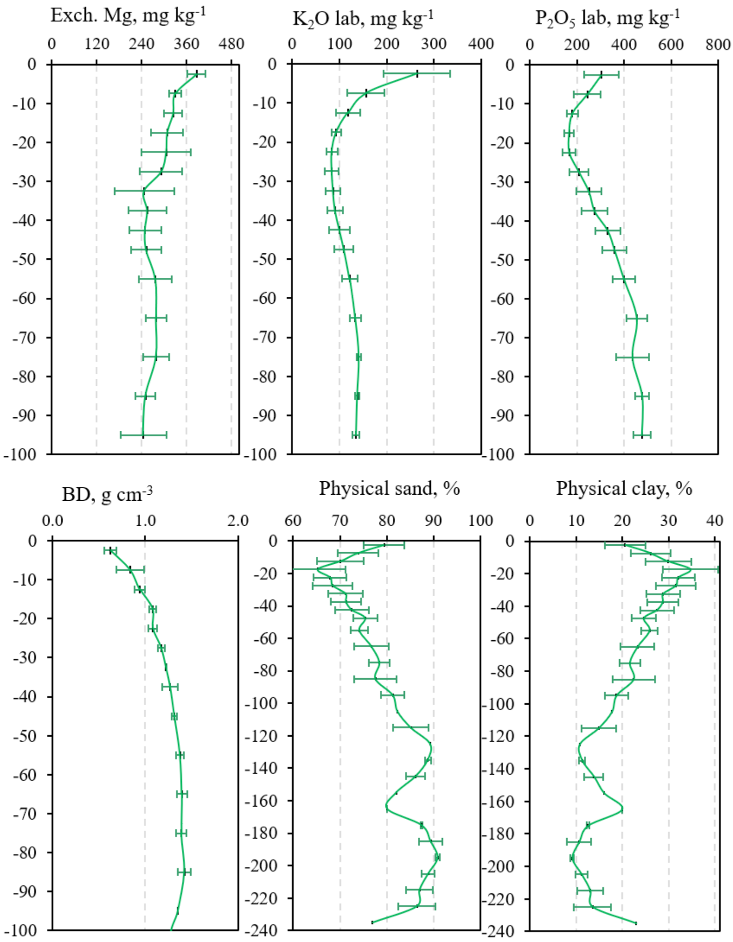

Figure 7. Continued from the previous page.

The soil's organic and inorganic carbon stocks at various depths were calculated based on data from the five soil profiles studied (see Figure 8). More than half of the carbon is stored in the top 30 cm of soil. Below this depth, down to 100 cm, the carbon stock amounts to 42% of that found in the top 30 cm. In the 100–200 cm layer, the carbon stock constitutes just 19% of that in the 0–30 cm layer. However, when inorganic carbon is included, the total stock in the 100–200 cm layer accounts for 76% of the stock in the 0–30 cm layer. The morphology of carbonate pedofeatures indicates that part of the inorganic carbon pool is present as young neoformations that are potentially susceptible to dissolution.

Recent studies (Loiko et al. 2025; Raudina et al. 2025) have reported that Luvic Greyzemic Phaeozem carbon stocks are comparable to those in similar soils in the region. The highest carbon stocks in the hemiboreal forests of the region are found in Luvic Greyzemic Phaeozems in river valleys with lateral slope wetting. Corg stocks in these locations within the 0–100 cm layer can exceed 30 kg/m^2 (Raudina et al. 2025). Our data, alongside that which has been published, allow us to conclude that, in the native Phaeozems of the region, variability in Corg reserves in the 0–30 cm layer is lower than in the 50–100 cm layer. This important theoretical conclusion indicates that the soil horizons in the middle part of the Phaeozem profile are more likely to have a greater potential for carbon accumulation than the near-surface humus horizons.

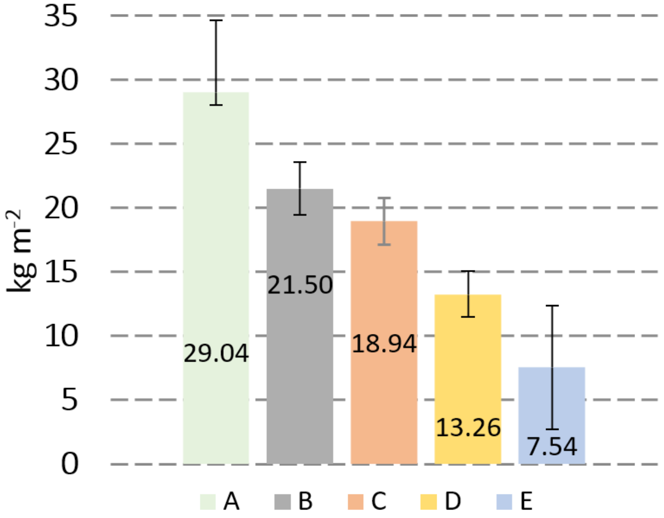

Figure 8. Average carbon stocks obtained for five profiles in the reference Luvic Greyzemic Phaeozem. **A** – Ctot in 0–200 cm. **B** – Corg in 0–200 cm. **C** – Corg in 0–100 cm. **D** – Corg in 0–30 cm. **E** – Cinorg in 0–200 cm.

The considerable stock of total carbon (Ctot) in the middle and deep horizons of the Luvic Greyzemic Phaeozem makes long-term monitoring of its status important, employing the space-for-time substitution approach. There is increasing attention being paid to the role of inorganic carbon in the carbon cycle (Alekseev et al. 2024). When soils are converted for agricultural use, it is believed that the carbon in deep soil horizons becomes more vulnerable for two reasons. The first is acidification due to the application of nitrogen fertiliser, and the second is the addition of fresh organic matter, which stimulates the mineralisation of ancient compounds (Jackson et al. 2017; Pries et al. 2023; Huang et al. 2024). However, the penetration of fresh organic matter via roots (Fernando et al. 2024) will also contribute to the stabilisation of some carbon, so the net trend is unclear. Due to the higher variability of deep soil carbon stocks, more robust sampling is required to draw reliable conclusions.

According to the theoretical principles underpinning the creation of Soil Red Books, the reference pedons studied fit into one of the following categories: 'reference soils – monitoring objects' (Antsiferova 2024). Work is currently underway at a regional level to compile such registries (Prokashev et al. 2021). The work carried out here could inform the decision to include this soil in a future Red Book of Kuzbass soils.

Conclusion

This study provides a thorough morpho-analytical characterisation of a rare, well-preserved native soil, which is classified as a Luvic Greyzemic Phaeozem (dark grey, super-deeply bleached soil). This soil is found in the southern taiga zone of south-eastern Western Siberia. The soil profile investigated at the 'Ust-Sosnovka' site is a vital reference point as it has developed over centuries without agrogenic impact under a unique tall herb aspen forest.

Key findings confirm that this ecosystem exhibits features of an old-growth forest with high biological activity. This results in a thick, bioturbated profile characterised by low bulk density (0.6–0.7 g/cm^3), Terromull humus and high natural fertility. The absence of a relic second humus horizon and the distribution of organic carbon within the profile indicate a state of progradation, whereby the soil actively accumulates and translocates organic matter downwards.

A significant outcome of the research is the quantification of substantial carbon stocks, over half of which are located in the top 30 cm of soil. Crucially, the research emphasises the significance of the inorganic carbon pool in the deeper horizons (100–200 cm), accounting for 76% of the total carbon stock in the top 30 cm. The morphology of carbonate neoformations indicates that this pool is dynamic and that both inherited and newly formed calcite are subject to dissolution and leaching processes in a humid climate.

The characterised soil profile is essential for assessing the extent and direction of agrogenic transformation in analogous soils converted for agricultural use over centennial timescales. In the context of carbon neutrality initiatives and sustainable land management, conserving and monitoring such reference sites is paramount. Therefore, we recommend including this unique Luvic Greyzemic Phaeozem pedon in regional soil protection registries, such as a prospective Red Book of Soils for the Kuzbass region.

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