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GENESIS AND GEOGRAPHY OF SOILS

Soils with the Second Humus Horizon, Paleochernozems, and the History of Pedogenesis at the Border between Forest and Steppe Areas

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Abstract—The genesis of soils with the second humus horizon (SHH)—the most striking relict feature in the profiles of soddy-podzolic (Retisols) and gray (forest) soils (Luvisols)—is discussed. The Middle Holocene radiocarbon age of the SHH, its dark color, and the discrepancy of its properties and the properties of modern humus horizons of forest soils have specified the main issues in the study of SHH: the character of climate changes and shifts of the boundaries of natural zones in the Holocene and the reflection of these changes in the evolution of the soil profiles. We consider the history of studies, systematization, geographic distribution, and modern properties of the SHH. On the basis of the analysis of Holocene paleosols, we try to characterize the prototype of the SHH, to estimate its age, and to trace stages of its development in the Holocene. We have also tried to find analogous soils with the SHH outside of Russia. According to the accepted hypothesis, SHHs are residual paleoclimatogenic formations. Other hypotheses consider them as buried horizons, a result of paleohydromorphism, etc. Dark humic substances of SHHs were formed in the first half of the Holocene and are characterized by extremely high stability. This allows them to survive in the aggressive environment of the eluvial horizons of Retisols and Luvisols. Under the influence of biochemical and mechanical (tree uprooting) factors, SHHs are strongly transformed, which complicates their study. At the same time, well-preserved Chernozems and dark-colored Phaeozems buried under kurgans and other earthy structures and sediments make it possible to establish the prototype of the SHH and to trace its degradation in the late Holocene. Within the East European Plain, the thickness and age of the SHH vary in agreement with the hypothesis of the residual paleoclimatogenic genesis of this horizon. The validity of the hypotheses of the buried nature and hydrogenic origin of the SHH is discussed. At present, interest in soils with the SHH in Russia has somewhat weakened. In Central Europe and North America, soils with the SHH have not been studied, but research into the problem of relict chernozems is being actively pursued. In our opinion, the combination of these two types of objects and, accordingly, the directions of research can lead to more definite conclusions about the origin and evolution of soils with the SHH.

Keywords: evolution of soils, Holocene, burial mounds, relict horizons, paleosols, radiocarbon age of soils

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INTRODUCTION

The second humus horizon (SHH) is the most widespread and pronounced relict (inherited) feature in soddy-podzolic, gray (Retisols, Luvisols),[1] and other modern soils with a texture-differentiated profile in the central parts of the East European Plain and West Siberian Lowland, as well as in some other regions [2, 16, 23, 25, 57, 64, 65]. The SHH occurs in the lower part of the eluvial horizon, or in the upper part of the illuvial horizon of these soils, at depths from 15–25 to 70–80 cm, in some cases up to 100 cm. Since the beginning of the 20th century, many hypotheses explaining the formation of this striking feature have been suggested. In addition to the initial point of view, according to which SHH is a residual paleoclimatogenic horizon, other theories of its origin were proposed. Thus, turbational, buried, paleohydrogenic, postcarbonate, and other kinds of SHHs were distinguished (typology according to [28]). In comparison with the hypothesis of paleoclimatogenic origin of the SHH, other hypotheses are less substantiated. In particular, this refers to the hypotheses of the burial of SHH and their formation under the impact of various soil turbation processes (the latter hypothesis is less discussed). Note that in the case of SHH burial (e.g., by fluvial or turbation processes), several such

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[1] Soil names are given according to the Russian soil classification system and the WRB [32, 85].

horizons can be formed (second, third, fourth humus horizons, etc.). Thus, the term second humus horizon can be applied to such horizons only conditionally.

In terms of its color and composition, the SHH does not correspond to the nature of modern pedogenesis. Another problem is closely connected with the problem of the genesis of SHH—the problem of paleochernozems found within the forest zone [39, 90]. According to the dominant hypothesis, these soils, as well as SHHs, are considered paleoclimatogenic formations. However, at present, there are significant discrepancies between different reconstructions of changes in pedogenesis and bioclimatic conditions in the Holocene: from complete denial of such changes to unambiguous adherence to the Blytt–Sernander scheme of climatic periods [36, 63]. In this regard, it seems that the study of such relics as the SHH and paleochernozems, which are not characteristic of the nature of pedogenesis in the forest zone, should significantly contribute to our knowledge of the evolution of soils and the environment in the Holocene [3, 42, 43, 60, 88]. The problems related to the origin of soils with the SHH are large and varied. In this review, we discuss the following issues: history of study of the soils with SHH, systematization of SHHs, hypotheses of SHH formation, geographic distribution of the soils with SHH, and characteristic morphological features and analytical properties of SHHs. The significance of paleosols buried under kurgans (burial mounds), in floodplain sediments, and in the depressions of the relief for elucidating the prototypes of SHH is also discussed. Analogues of soils with the SHH outside Russia are briefly considered. Stages of the evolution and age of SHHs, the stability of humus in these horizons, and the processes of degradation of the SHH in the modern soils are analyzed.

HISTORY OF THE STUDY OF SOILS WITH THE SHH

The horizon under consideration, which is now called the SHH, was first described in 1914 in the profiles of soddy-podzolic soils of Western Siberia [16] and gray forest soils of the North Caucasus [64, 65]. Then, SHHs were found in soils on the East European Plain [23, 57]. According to data for the mid-1980s, the area of soils with the SHH expanded significantly; such soils were described over large areas from the forest-steppe to the middle taiga subzone in the Western and, partly, Central Siberia; in the East European Plain, they were found from the north of the forest-steppe zone to the northern taiga subzone [29, 57]. Later, they were also found in the typical and southern forest-steppe in the center of the East European Plain [60].

Initially, these soils were called differently: secondary podzols [16], gray forest soils over chernozem [64, 65]. In their main northern area, they were called secondary podzolic soils [23, 24]. Despite the natural differences between these soils because of sharp differences in the environmental conditions—shallow depth of SHH in the north and its deep position in the south (North Caucasus)—their genesis was independently explained in a similar way: degradation processes that led to the destruction of the upper part of the humus profiles of previously formed soils. The hypotheses advanced by Dranitsyn and Yakovlev were based on the idea about the evolution of soils and soil cover. In that period, Dokuchaev's pedology was developing, and ideas about the evolution of soils over time and soil transformation in relation to changes in the environmental conditions were quite natural. In fact, these ideas were advanced by Dokuchaev [14, 15] and other researchers [18, 33, 34, 46, 79, 80].

The term second humus horizon (SHH) appeared later, for example, in [40]. In our opinion, this term is not quite appropriate for the considered phenomenon. It presupposes an expansive interpretation going far beyond the originally identified objects, i.e., soils of forest genesis with an inherited (residual) dark humus horizon formed under different conditions, in steppe or grassland environments. With the approval of the term SHH and its inclusion in the soil classification system, its interpretation became even wider; this term was applied to the inherited humus horizons, buried humus horizons, recent illuvial humus horizons, and to geological relics of other epochs not related to the Holocene evolution of the considered soils. We argue that the term residual humus horizon [17] would be more appropriate.

SYSTEMATIZATION OF SHHs AND HYPOTHESES OF THEIR ORIGIN

The most complete systematization of SHHs is given in [28, 29]. In these works, the inherited paleoclimatogenic soil formations were referred to as SHHs proper. In our paper, we consider the origin and distribution of soils with the SHH mainly from the standpoint of this initial hypothesis, as a paleoclimatic relic (residual, inherited, associated with the degradation of the upper part of the original dark-colored horizon). Similar approach is developed in [23, 25, 26, 41, 44, 53, 57].

Based on these ideas, the following definition of the SHH can be given: SHH is a dark-colored horizon lying in the profiles of soddy-podzolic, gray (Retisols, Luvisols), and some other soils within the eluvial (E) horizon and/or within the upper part of the illuvial Bt horizon, at depths from 15–25 to 70–80 cm (sometimes, up to 100 cm), which is not a buried horizon; it is a residual formation inherited from the original dark-humus A horizon of Chernozems or dark-humus Phaeozems and containing stable forms of humus differing from those in the modern gray-humus A horizons forming under forests.

At the first stage of the study of soils with the SHH, two main stages of their formation (steppe and forest) were identified, but the age of these soils was determined presumably. Subsequently, these stages were tied to the stages of development of the natural environment in the Holocene, which was facilitated by the development of paleogeography, ideas about the age of soils, and methods of their dating [9, 58, 62, 98]. Initially, paleopedological data were of great importance in constructing schemes for the evolution of the environment in the Holocene [9]. An important role in them was played by the results of studying soils with relict dark-colored horizons, but then the methods of paleobotany played the major role [38, 48, 58, 71, 74].

The number of works devoted to soils with the SHH is extremely large; in this paper, only the most significant and influential studies are mentioned. In the majority of works, SHHs are interpreted as relict residual paleoclimatogenic formations [3, 11, 13, 16, 19, 23–25, 33, 41–43, 46, 47, 54, 60, 64, 65]. Sometimes, the genesis of the residual horizons is explained by changes in the hydrological regime because of the development of the relief or tectonic movements [31, 40, 56]. In a number of works, the SHH is considered a buried relic [36, 49].

The problem of Holocene chernozems that are often found within the forest zone (e.g., chernozems of the Vladimir opolie [37, 39, 52]) is close to the problem of soils with the SHH. In the areas of forest soils (Luvisols), paleochernozems have also been found in Central Europe [88, 90]. There, as well as in Russia, chernozems are found under kurgans (burial mounds) of the Neolithic and Bronze ages, now under the forest [3, 60, 78, 83, 86]. These soils are of great importance for understanding the history of pedogenesis in the Holocene and, in particular, display those prototypes [44] that served as the basis for the formation of soils with the SHH and allow us to elucidate the nature of the evolution of the initial chernozems into soils with the SHH.

It should be noted that, despite the long history of studies of the SHH phenomenon, its genesis is still debatable, and the evolution of soils at the forest/steppe border is a matter of discussion. With the appearance of alternative hypotheses of the genesis of SHHs, interest in this problem somewhat decreased, which is obviously associated with an increase in the complexity of the problem and the impossibility of solving it based on the use of traditional research methods. In our opinion, to obtain more definite results, it is necessary to use methods of related sciences: paleopedology, paleogeography, and archaeological soil science [22, 51].

DISTRIBUTION OF SHHs

Second humus horizons have been found in soils over vast areas [57] and under different climatic conditions. The distribution of residual SHHs is limited by bioclimatic and lithological factors, the first of which determined the general patterns of the SHH and the second contributed to different degrees of preservation of the SHH in modern soils at the regional and local levels.

1. Bioclimatic factors. Temperature and precipitation differ in the area of soils with the SHH, but the ratio between temperature and atmospheric precipitation is relatively stable and corresponds to the transition from forest to steppe. The area of SHHs stretches in the form of a wide strip along the southern border of the forest zone, across the East European Plain and West Siberian Lowland and, in the form of separate islands, in Central Siberia and the Far East [57]. The second, narrower, strip runs along the foothills of the North Caucasus (Fig. 1).

2. Lithological conditions and relief play an important role in the development and preservation of SHHs. These horizons are mainly found in soils developing from mantle loams and loess. In some cases, SHHs can be found in soils developing from moraine deposits and loamy alluvium; they are absent in sandy soils. Also, great difficulties in the study of SHH and paleochernozems arise when the thickness of loams is low, and they are underlain by sand or red-colored rocks. The preservation of SHH depends on the topographic conditions, which determine the hydrological regime of soils, and on the soil texture. For example, studies in Novosvobodnaya (Adygea) showed that the preservation of SHH increases in soils developed from heavy-textured parent materials, in the profile of which organo-mineral bonds become stronger, as well as in areas with weakened drainage, within which even a slight increase in anaerobic conditions weakens the microbial decomposition of soil OM [3]. In the case of close embedding of the soil with lithogenic carbonates (calcareous rocks), the stability of humus in the SHH increases even more.

Within the vast area of soils with the SHH (East European Plain, Western Siberia and the North Caucasus), its maximum degree of expression is characteristic of light gray and gray forest soils (Albic Luvisols, Luvic Phaeozems); to the north and south of their range, the SHH becomes less pronounced. Thus, in the soddy-podzolic and podzolic soils, the SHH becomes lighter and thinner, up to its complete disappearance. In the subzone of clay-differentiated chernozems (Luvic Chernozems), the SHH is not visible, because it is included in the modern humus profile [35]. It should be noted that not only along the periphery of the area of SHH but also within its core area—a wide strip from the Carpathian region to the Yenisei River—the distribution of SHH is discontinuous, intermittent, which is associated with the heterogeneity of the factors of its formation and degradation.

Bioclimatic conditions differ significantly within a large area of soils with the SHH. This predetermined

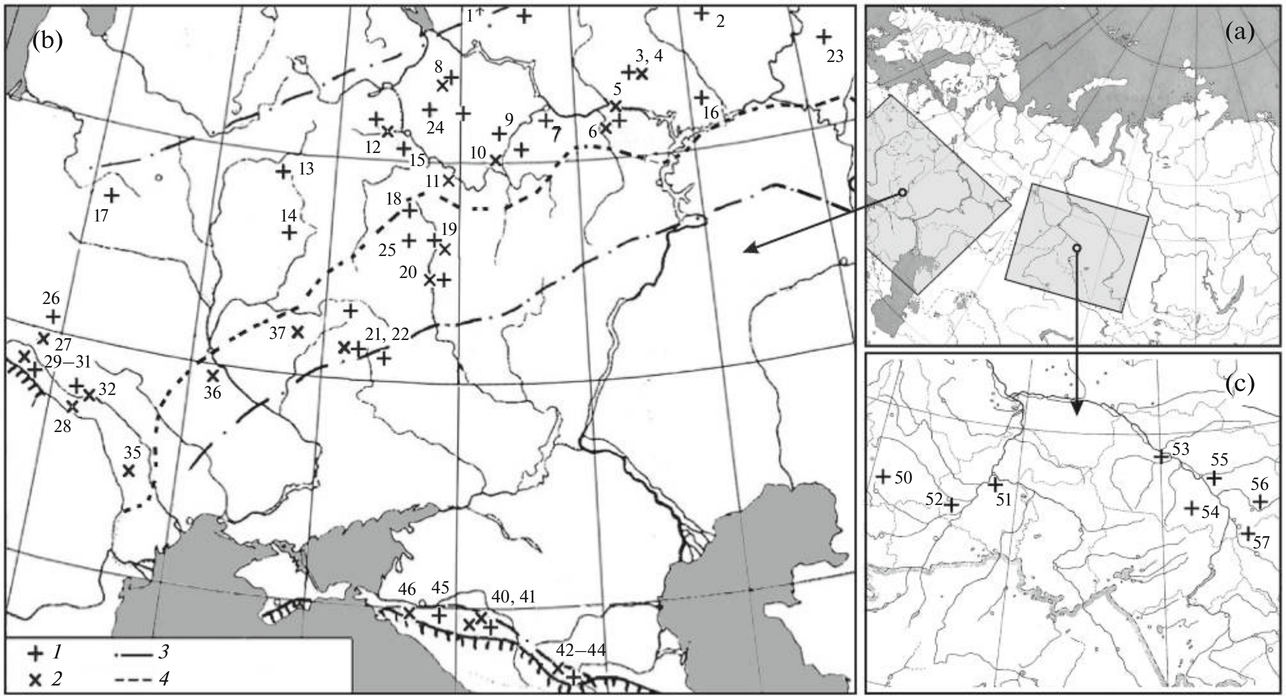

Fig. 1. Distribution of SHH and dark-colored paleosols (according to the authors' materials and other sources): (a) main study areas, (b) East European Plain, and (c) West Siberian Lowland; *1*—soils with SHH, *2*—buried chernozems and dark humus soils, *3*—area of SHH, and (*4*) border between broadleaved forest and forest-steppe zones. Numbers on the map: (1) Totma [28], (2) Yaransk, (3) Aleevo, (4) Prokop'evo, (5) Vilovatovo, (6) Atlikasy, (7) Nizhny Novgorod, (8) Rostov Velikii, (9) Murom, (10) Izhevskoye, (11) Ryazan, (12) Ranis, (13) Smolensk, (14) Roslavl (data of Dolgova, 1964), (15) Podol'sk, (16) Malmyzh, (17) Novogrudok, (18) Kulikovo Field, (19) Perekhval, (20) Voronezh, (21) Borisovka, (22) Shebekino, (23) Kungur [23], (24) Tiribrovo, (25) Efremov, (26) Podgortsy, (27) Sarniki, (28) Sadgora, (29) Dashava, (30) Truskavets (data of Sulimirski, 1968), (31) N. Strutin, (32) Troyan Val, (35) Kodry, (36) Kruglik, (37) Romny, (40) Novosvobodnaya, (41) Bogatyrskaya Polyana, (42) Nal'chik (Kulikov's data), (43) Urvan', (44) Chikola, (45) Vochepshii, (46) Azovskaya, (50) Yekaterinburg, (51) Tobolsk, (52) Tyumen, (53) Vasyugan [24], (54) Andarma [24], (55) Ket' [24], (56) Chulym [25], and (57) Tomsk.

the diversity of the original dark-colored soils, and soils with the SHHs derived from them. In the north, where the activity of soil biota is weakened, the original dark-colored horizons were shallow; therefore, the SHHs lie close to the surface. Thus, in podzolic soils of Vologda oblast, SHHs appear in the form of mottles already at a depth of 6 cm [28]. In southern regions, they lie much deeper—in the second half of meter (Fig. 2), which is consistent with the development of deep initial chernozems in this area [4]. It is interesting that geographically determined differences are manifested not only in the thickness and depth of the SHH and its prototypes but also in their age.

In addition to the residual climatogenic SHHs proper, the age and depth of which corresponds to the geography of factors and processes of their formation, buried and turbated variants of the SHH locally occur; their age and depth may be different.

MODERN PROPERTIES OF THE SHH

True paleoclimatogenic SHHs are characterized by a set of morphological and physicochemical properties. The analysis of our own and literature data indicates that the SHHs are strictly confined to the particular stratigraphic position: they are present in the light material of eluvial (E) horizon, mostly in its lower part; in the case of the deep initial humus horizons, they may be found in the upper part of the Bt horizon [25, 43]. In the North Caucasus, dark well-preserved SHHs lie in the deep part of the Bt horizon (60–100 cm). However, some signs of degraded dark-colored humus are also seen in the lower part of eluvial (E) horizon. Often, poorly preserved SHH variants are characterized by a mottled color pattern. Except for the dark color, other morphological properties of the original humus horizon—crumb structure, bulk density, pedofeatures—have not been preserved. The modern properties of the SHH correspond to those horizons of the modern soil profile, in which it is located [25, 41, 44].

Owing to the long-term occurrence of the SHH in an aggressive (acidic) medium in the part of the profiles of podzolic, soddy-podzolic, and other soils with a texture-differentiated profile (Retisols, Luvisols)—in the E horizon or in the upper part of the Bt horizon—not only morphology but also physicochemical properties of the initial humus horizon are strongly transformed. Usually, the SHH has a high acidity,

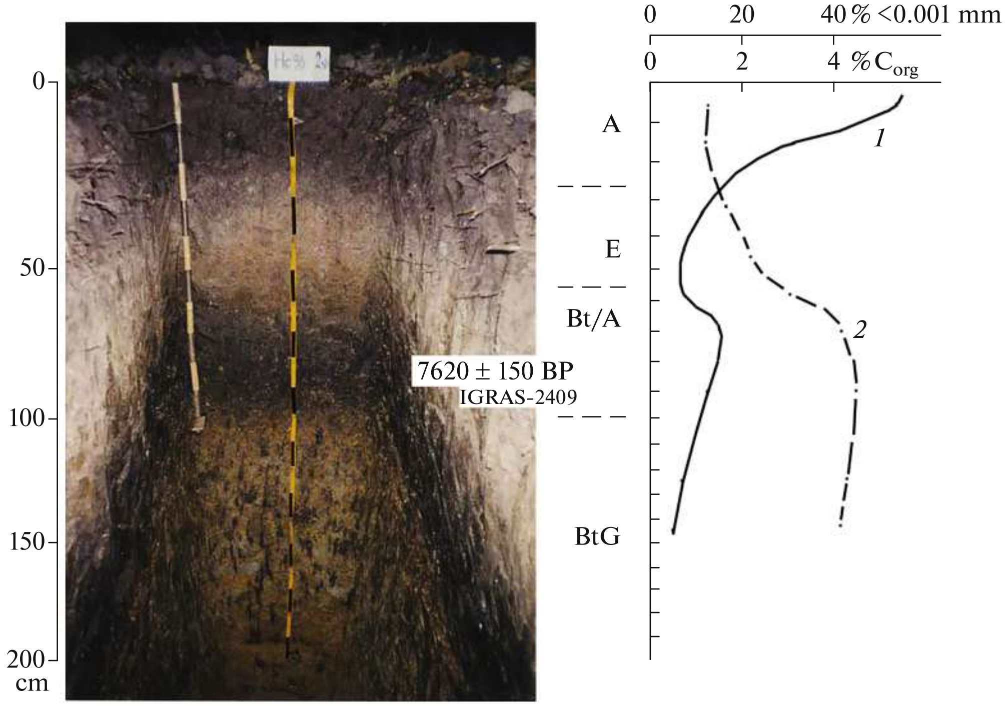

Fig. 2. Radiocarbon age, humus content, and clay content in the profile of gray soil with SHH, Novosvobodnaya site, North Caucasus.

platy structure (within the AE, E, and EB horizons) and blocky prismatic structure within the Bt horizon. In the microstructure of the SHH, dark-colored clots of the mull humus are preserved and are clearly seen against the background of light-colored eluvial horizons [12, 30]. The degree of transformation of the original dark-colored soils is very high. Even such stable properties as the thickness of the horizon, bulk density, and particle-size distribution are subjected to changes. The study of paleosols located at a greater depth than the SHH showed that only unstable properties and characteristics (pH, exchangeable cations, content of salts and pedogenic carbonates [2]) are completely transformed in them. The preservation of humus horizons in the paleosols is better and generally depends on the genetic type of soil. The gray-humus horizons characteristic of soddy-podzolic and gray soils are destroyed quickly, over hundreds of years. Dark-humus horizons, especially the Ca-humus horizons of chernozems, are more resistant to transformation, but they also degrade in some cases. The organic matter of dark-colored SHHs is relatively stable; with respect to this characteristic, it is close to the organic matter of chernozems. However, despite the high degree of stability of SHHs, they are gradually transformed under the impact of eluviation processes in the E horizon and illuviation of clay–humus materials in the Bt horizon [25]. Locally, SHHs are destroyed by the soil turbations associated with uprooting of the trees.

As a result of degradation of the SHH, the C_{org} content in it decreases despite the dark color; often, it does not exceed the values in the light-colored eluvial horizon [25]. This is due to the loss of unstable fractions of organic matter and the preservation of stable fractions, which provide for the dark color of the SHH (probably, because of the presence of humin). Despite such a decrease in the C_{org} content attesting to a strong transformation of soil organic matter, the radiocarbon dating of samples of humic acids from such degraded SHHs often yields ancient radiocarbon dates close to those for slightly degraded SHHs. According to our data, iron oxides are of great importance in the preservation of the SHH because of their participation in bonding of the organic matter with the mineral soil mass. However, an increase in the soil moistening and gley processes lead to the destruction of these bonds, iron leaching, and the loss of the dark humus color. In the case of a strong degradation of the SHH, the contents of humus and nitrogen in it decrease to values typical of the E, EB, and Bt horizons. At the same time, some humus coloring is still preserved. It should be noted that such an important issue as changes in the composition of humus in the SHH remains insufficiently studied; new research methods should be applied to characterize these changes in detail.

As the SHH lies in the transitional zone from the eluvial to the illuvial horizons, its particle-size distribution changes: the upper part of the SHH is clay-depleted, whereas its lower part is less depleted in clay and often contains morphologically visible features of clay illuviation. Changes in the texture and other properties also occur in the underlying soil horizons. As a result of leaching of carbonates and subsequent lessivage, the original Bk horizon becomes carbonate-free and thick clay coatings are formed in it. Gradually, this horizon acquires the features of the Bt horizon. The clay content in it is two times higher than that in the newly formed eluvial horizon. Mole tunnels (krotovinas) are gradually erased, though, in most cases, their stability is higher than that of the SHH itself.

The composition of humus in the SHH of soddy-podzolic soils (Retisols) changes over time to fulvate type, but a high proportion of the second fraction of humic acids is preserved [8, 25, 27]. In many cases, according to the composition of humus, the SHH can be classified as a humate-calcium horizon [27]. Analogous properties of the organic matter are characteristic of the dark-humus horizons of the chernozems. of chernozems and do not occur in the gray-humus horizons of soddy-podzolic soils and other soils of the forest zone.

The radiocarbon age of the SHH is the most important feature that confirms the relict nature of the horizon and makes it possible to unveil the Holocene history of soil development [11, 12, 17, 28, 42]. Radiocarbon dating of the fractions of organic matter from the SHH attests to a regular increase in the age from the first to the second and further to the third fraction of humic acids [43, 44]. Cases of significant rejuvenation of humus should be noted, especially for the shallow-lying and strongly degraded SHHs. In the pit 2-71 (demonstrated by V.O. Targulian during the excursion of the X International Congress of Soil Science), the relict SHH was poorly preserved in the E and EB horizons. However, the age of humic acids from it reached 4440 ± 30 BP (IGAN-65). In the adjacent pit 2-71a, the SHH was better preserved, and the age of humic acids was noticeably greater: 5860 ± 60 BP (IGAN-64) [2]. In the Tobolsk region in Western Siberia, the degree of HA rejuvenation is higher and the difference between the dates obtained from poorly and well-preserved SHHs was even greater: 1910 ± 120 versus 3340 ± 80 BP (Ki-19279 and K-19280). In general, radiocarbon dates characterize the age of humic acids in the older lower part of the original humus horizon, but they are rejuvenated because of the shallow occurrence of the SHH. At the same time, the degree of rejuvenation of the dates is small and their main array confirms the assignment of the SHH to the Middle Holocene (in some cases, the Early Holocene).

It is known that the ^{14}C dates obtained from the soil organic matter (from humic acids or from the total organic matter) do not characterize the time of the beginning of soil formation and, in the case of paleosols, the time of the paleosol burial. They characterize the mean residence time of carbon in the soil [92]. Therefore, the radiocarbon dates obtained from the SHH and even groups of such dates, are always younger than the time of the beginning of the formation of the dark-humus horizons. More precisely, the time of formation of dark-colored SHH prototypes can be determined from the results of studying the buried soils.

Paleokrotovinas are important indicative features making it possible to characterize the conditions of pedogenesis [93]. In some cases, in soils with the SHH, there are krotovinas left by mole rats or other steppe earth burrowers [67]. These krotovinas are large and deep, which is typical for the soils of the steppe zone regions [94]. Such krotovinas are more completely presented in buried chernozems and other paleosols associated with soils with the SHH [69, 76]. In some cases, in the Bt horizon of Retisols, paleokrotovinas filled with the dark-colored SHH material are found, although the SHH itself is already severely destroyed [2]. Thus, the date 7570 ± 40 BP (IGAN-402) was obtained from a krotovina in the soil with the SHH (in the Malaya Istra River catchment).

INITIAL SOILS—PROTOTYPES OF THE SHH

Reconstruction of the original soils, which served as the basis for the formation of the SHH, is a difficult challenge. For this purpose, we studied in detail the SHHs themselves and their location in the soil profiles and in the soil cover [17, 24, 25, 41, 43]. It was found that different soils could be the prototypes of the SHH; these soils constituted a heterogeneous initial soil cover, but all of them were characterized by dark-humus horizons (Table 1). To reconstruct the original soils, we used data on the depth of the lower boundary of the SHH, as well as on variations in this depth for catenas and soil cover elements [25]. As a result, the following prototypes were distinguished: chernozems and gray forest soils, soddy soils, dark-humus soils, meadow chernozems, and meadow soils [25, 44]. Undoubtedly, the initial soil cover, which served as the basis for the formation of soils with the SHH, contained not only soils formed under autonomous mesomorphic conditions (Chernozems, Phaeozems) [2, 25–27, 43, 60, 61] but also soils of depressions with pronounced hydromorphism. The same pattern is typical of modern chernozemic areas: quasigleyed chernozems (meadow-chernozemic soils) of depressions occur amidst automorphic chernozems. Similar variants of soils adjacent to soddy-podzolic and gray soils containing SHHs have been studied [25, 26, 43, 44].

At the same time, there are ideas about the predominantly paleohydromorphic origin of the SHH [17, 31]. In particular, in support of the hypothesis of the paleohydromorphic origin of the SHH prototype, data from phytolith analysis of the SHH are available [7]. In our opinion, the preservation of phytoliths for millennia in the shallow-lying SHH seems unlikely. Most likely, the phytoliths discovered by the author appeared during the latest stage of pedogenesis

Table 1. Soils with the SHH, their age, environmental conditions, and associated buried soils of archaeological sites (burial mounds and ramparts)

Location of study sites	Modern biomes. Mean annual temperature, (°C) and precipitation (mm/yr)	Modern soils; depth of SHH, cm	Paleosols; name, depth*, cm	^{14}C age of relict SHH ($_{rh}$) and paleosol ($_{p}$), yr BP (uncalib.); laboratory codes are given in Table 2	Reconstructed calibrated age of the dark-colored stage, (ka BP)	Reference
East European Plain						
Tot’ma, Vologda oblast	Middle taiga. +2.6, 615	Podzolic, 6–22	Humus-accumulative***	$7990 \pm 150_{rh}$	Early Holocene	[28]
Yaransk, Kirov oblast	Southern taiga. +2.9, 600–620	Soddy-podzolic, 14–24(30)	Dark humus**	$5530 \pm 160_{rh}$ $7630 \pm 390_{rh}$ $8630–6500_{rh}$	10–5	[43]
Aleevo, Mari-El, kurgans ca. 4000***	Southern taiga–subtaiga. +3, 550	Soddy-podzolic, 9–18	Gray to dark gray**** with carbonate horizon, 0–23	–	10–4	[3]
Vilovatovo, Gornomariyskii district of Mari-El, kurgans 4000	Broadleaved forests. +3.1, 550	Soddy-podzolic, 20–40	Dark gray**** with carbonate horizon, 0–43	$6440 \pm 150_{rh}$ $5550 \pm 150_{p}$ $8190 \pm 90_{p}$	10–4	[3]
Atlikasy, Chuvash Republic, kurgan of the Bronze Age, ca. 4000	Broadleaved forests–forest-steppe. +3, 540	Gray, 20–40(60)	Clay-illuvial chernozem, 0–60	–	12–2	[3]
Izhevskoe, Ryazan oblast, kurgan of the Bronze Age, ca. 4000	Broadleaved forests. +4, 500–520	Gray, 45–60	Chernozem, 0–65	$5690 \pm 110_{p}$ $5830 \pm 110_{p}$	8–4	Alexandrovskiy, unpublished data
Borisovka, Belgorod oblast, rampart of ancient settlement, ca. 2350	Forest-steppe. +7, 600	Gray, 25–55	Chernozem, 0–40	$6080 \pm 150_{p}$	> 10–1.7	[76]

Table 1. (Contd.)

Location of study sites	Modern biomes. Mean annual temperature, (°C) and precipitation (mm/yr)	Modern soils; depth of SHH, cm	Paleosols; name, depth*, cm	^{14}C age of relict SHH ($_{rh}$) and paleosol ($_{p}$), yr BP (uncalib.); laboratory codes are given in Table 2	Reconstructed calibrated age of the dark-colored stage, (ka BP)	Reference
Western Siberia						
Tobolsk	Southern taiga. –1, 480	Soddy-podzolic, 15–30	Dark humus^2	3340 ± 80_{rh}	10–4(2)	Yurtaev, unpublished data
Tomsk	Subtaiga. –1, 560	Soddy-podzolic, 30–50	Chernozems, gray forest, meadow-chernozemic, etc.^{2}; 28 to 58^2	4000–8600_{rh}	10–4	[25, 26]
CisCarpathians						
Sarniki, mound, about 3500	Broadleaved forests. +7, 800	Gray, 35–85	Chernozem, 0–60	5320 ± 120_{rh}	>10–4	Alexandrovskiy, unpublished data
Troyan Val, ancient settlement 2350	Forest-steppe. +9, 715	Gray 35–85	Chernozem, 0–85	5030 ± 120_{rh} 3420 ± 70–7650 ± 120_{p}	>10–<2	[3]
North Caucasus						
Novosvobodnaya, Adygea, kurgans 5000–5300	Broadleaved forests. +10, 800	Gray, 50–100	Chernozem, 0–85	7130 ± 40_{rh} 6455 ± 100–9785 ± 580_{p}	12–4	[69]
Bogatyrskaya Polyana, Adygea. Rampart of the settlement, 2300	Broadleaved forests. +9, >800	Gray, 60–100	Clay-illuvial chernozem (degraded), 0–100	–	12–<2 ka	Alexandrovskiy, unpublished data
Urvan, Kabardino-Balkaria. Kurgan of the Bronze Age, ca. 4000	Forest-steppe. +9.5, 850	Gray, <83	Chernozem, 0–55	–	12–<2	[4]

* The depth of the A + AB horizon (from the surface of the buried soil).
** Reconstructed according to the SHH.
*** Age of kurgans and settlements in years.
**** With SHH.

in the Late Holocene. Their accumulation was facilitated by the cooling and humidification of the climate, and the associated active spread of mires in Western Siberia and other territories [26]. The possibility of fast transformation of the phytolithic profile of soils with the SHH is evidenced by the comparative analysis of phytoliths in buried dark gray soils of the Bronze Age and background soddy-podzolic soils with the SHH (middle Volga basin), as well as in soils buried under the ramparts of the Iron Age settlement in the upper Don reaches [10]. The materials given in [10, Figs. 2 and 3] clearly show that phytolithic spectra may be completely rearranged in relatively short period (hundreds of years) not only in the surface horizons but also at the depth of the SHH.

Long-term study of soils with the SHH has not led to a solution to the problem of their genesis. Probably, it is difficult to reconstruct the SHH prototype on the basis of studying only the modern profile, which includes only one relict horizon, which stands out only in color, and sometimes in the content and composition of humus, even using a large set of methods. The SHH lies at a shallow depth and is subjected to a long-term intense influence of the actual pedogenesis, as a result of which, despite the stability of humus, only the lower part of the original dark-humus horizon has been preserved (in some cases, krotovinas associated with this horizon). Data on the radiocarbon age of the SHH may be somewhat unambiguous. Sometimes, the dates are as old as the Early Holocene [43, 44]; sometimes, they are strongly rejuvenated. Owing to the shallow occurrence of the SHH, pollen and other components, the study of which could help in paleoreconstruction, are not preserved in the SHH. Therefore, a large role should be played by paleosols buried under kurgans, ramparts, or under alluvial sediments. Such buried paleosols make it possible to study the original soil profile in its entirety, as well as to obtain dates that are less distorted. At a great depth of burial of such soils, the original morphological and physicochemical properties, charcoal, and pollen are usually well preserved [67, 83, 86].

CHANGES IN THE BIOCLIMATIC CONDITIONS IN THE HOLOCENE AND THE SHH

Changes in pedogenesis in the Holocene were largely associated with changes in bioclimatic conditions [63]. Climate changes in the Holocene were not so great and did not cause such large-scale changes in the environment as in the Pleistocene. At the same time, general pattern of these changes is well known: warming in the Early Holocene, thermal maximum 5–6 ka BP, and cooling in the Late Holocene. The general pattern of climate changes in the Holocene is clearly presented in the diagrams [58, 59]. According to these data, the maximum temperatures were in the second half of the Atlantic period, and the maximum moistening was in the last quarter of the Holocene. In addition, smaller temperature fluctuations and significant regional differences have been found. In particular, differences in precipitation patterns in the East European Plain and in the north of Western Europe, for which the Blytt–Sernander climatic scheme was developed [1, 5, 9].

Before the appearance of this scheme, the concepts of the environmental evolution in the Holocene of Europe were different; they were largely based on the results of studying soils with relict dark-colored horizons. According to studies in Eastern Europe, it was assumed that during the thermal maximum, the humidity of the climate decreased and soils with thick dark horizons moved to the north. During the Late Holocene cooling, the climate became more humid, which caused the displacement of natural zones to the south [9]. According to palynological data obtained mainly from peatlands and lacustrine deposits, traces of the presence of steppe or forest-steppe vegetation within the modern zone of soils with the SHH are less common, though they can be found in the literature [38, 48]. In [38], data are given on two periods of the advance of forest-steppe vegetation far to the north, in the basin of the Severnaya Dvina River (modern middle taiga) in the Middle Holocene.

Similar schemes for changing soils and landscapes were common in Western Europe [82, 89, 100, 101], but then the Blytt–Sernander scheme became the main one. At present, the concept of an arid “chernozem” thermal maximum of the Holocene is being developed mainly on the basis of paleopedological studies [81, 90]. Note that in North America, the Blytt–Sernander scheme did not receive support, and the concept of a lower climate humidity during the Middle Holocene thermal maximum remained the dominant concept [73, 74].

THE IMPORTANCE OF PALEOSOLS FOR UNDERSTANDING THE EVOLUTION OF SOILS WITH THE SHH

In the East European Plain, in the area of soils with the SHH (Middle Volga reaches, CisCarpathians, and North Caucasus), modern forest landscapes with well-developed soddy-podzolic and gray soils are marked by the presence chernozems and other soils with dark-colored humus horizons buried under kurgans, ramparts, alluvial sediments, and other sediments of the Holocene age.

Tables 1 and 2 show pairs represented by the buried paleosols and background surface soils with the SHH studied in the center of the East European Plain, in the CisCarpathians, and in the North Caucasus. Analogous data are available for other regions [3, Table 16]: in the Middle Volga basin (Prokop’evo, Yuvanovo, settlements of the Early Iron Age (Ernur, Yuvanovo, Romny)); CisCarpathians (Dashava, Strutin, Kodry);

Table 2. Properties and age of paleosols associated with the studied SHHs (Table 1) and reconstructed environmental conditions

Location of paleosol	Paleosol, depth, cm	Background soil with SHH	Additional paleosol features	^{14}C age of paleosol ($_p$), yr BP	Laboratory code	Reconstructed biomes/modern biomes	Reference
East European Plain							
Aleevo, Mari-El, kurgans 4000	Gray to dark gray carbonate, 0–23	Soddy-podzolic	Krotovinas. Carbonates from 70 cm (>250 cm in background soils)	–		Broadleaved forests/southern taiga	Aleksandrovskiy, unpublished data
Vilovatovo, Gornomariyskiy district of Mari-El, kurgans 4000	Dark gray carbonate, 0–43	Soddy-podzolic	Krotovinas. Carbonates from 80 cm (>270 cm in background soils)	$5550 \pm 150_p$ $8190 \pm 90_p$ $6440 \pm 150_{rh}$	IGAN-604 IGAN-602 IGAN-605	Broadleaved forests Broadleaved forests/forest-steppe Forest-steppe/broadleaved forests	[3]
Atlikasy, Chuvash Republic, kurgan of the Bronze Age, ca. 4000	Clay-illuvial chernozem, 0–60	Gray with SHH	Krotovinas. Carbonates from 75 cm (>170 cm in background soils)	–		Forest-steppe/broadleaved forests	[3]
Izhevskoe, Ryazan oblast. kurgan of the Bronze Age, ca. 4000	Chernozem, 0–65	Gray with SHH	Krotovinas. Carbonates from 100 cm (>190 cm in background soils)	$5690 \pm 110_p$ $6590 \pm 170_p$ $5100 \pm 90_{rh}$ $5960 \pm 110_{rh}$	IGAN-1216 Ki-19842, 19843, 19840	Steppe/broadleaved forests	Aleksandrovskiy, unpublished data
Borisovka, Belgorod oblast, rampart of ancient settlement, 2350	Chernozem, 0–40	Gray with SHH	Krotovinas. Carbonates from 46 cm (122 cm in background soils)	$6080 \pm 150_p$	Ki-19109	Steppe/forest-steppe	[76]
CisCarpathians							
Sarniki, kurgan of the Bronze Age, ca. 3500	Chernozem, 0–60	Gray with SHH	Moleholes. Carbonates from 105 cm/in background >370 cm	$5320 \pm 120_{rh}$	IGAN-1503	Forest-steppe/deciduous forests	Alexandrovsky, unpublished data
Troyan Val, ancient settlement, 2350	Chernozem, 0–85	Gray with SHH	Krotovinas. Carbonates from 90 cm (125 cm in background soils)	3420 ± 70– $7650 \pm 120_p$ $5030 \pm 120_{rh}$	IGAN-1060–1057 IGAN-1064	Steppe/forest-steppe	[3]
North Caucasus							
Novosvobodnaya, Adygea, kurgans, 5000–5300	Chernozem, 0–85	Light gray with SHH	Krotovinas, Carbonates from 85 cm (>150 cm in background soils)	$6455 \pm 100_p$ $9785 \pm 580_p$ $7130 \pm 40_{rh}$ $7620 \pm 150_{rh}$	IGAN-1215 IGAN-1154 IGAN-1084, 2409	Forest-steppe/broadleaved forests	[69]
Bogatyrskaya Polyana, Adygea. rampart of the settlement, 2300	Degraded chernozem, 0–100	Light gray with SHH	Krotovinas. Carbonates >150 cm	–		Forest-steppe/broadleaved forests	Alexandrovskiy, unpublished data
Urvan, Kabardino-Balkaria, kurgan of the Bronze Age, ca. 3500	Chernozem, 0–55	Gray	Krotovinas. Carbonates from 53 cm (83 cm in background soils)	–		Steppe/forest-steppe	[4]

and North Caucasus (Vochepshii, Chikola, Azovskaya, etc.). These soil pairs are mainly developed from loesslike loam and, less often, from alluvial sediments and occupy similar geomorphic positions. This is important, because these types of sediments are characterized by the spatial homogeneity, so the soils developed from them are comparable and reflect changes in the environment over time. On other rocks, the comparison of background surface and buried soils is complicated by the variability of the soil cover and the low sensitivity of soils to changes in the bioclimatic conditions.

A comparative study of buried paleosols and background surface soils with the SHH (Tables 1 and 2) has shown the following:

(1) The leveling survey indicates that the buried soil surface under the kurgans and ramparts of the fortified settlements corresponds to the level of the surrounding (background) territory [3]. Consequently, the soil surface level in the Holocene was stable, which refutes the hypothesis of the burial of the SHH under some sediments mantles covering large areas. Earlier, Zolotun came to a conclusion about the stability of the soil surface in the Holocene on the basis of leveling surveys of the surface of buried soils for a large number of kurgans [20].

(2) The radiocarbon age of the buried soils in the pairs under consideration is usually older than the age of the SHH. The dates of paleosols refer to the Atlantic, and in some cases to the Boreal and even Preboreal periods of the Holocene.

(3) In all cases, buried soils (prototypes of the SHH) are represented by more eutrophic and xeromorphic variants than soils with the SHH. Therefore, the assumptions about the predominantly hydromorphic genesis of the prototypes of SHH are not confirmed.

(4) The soils buried under the kurgans and ramparts are represented by dark-humus horizons and usually contain a high-lying carbonate horizon, while the background soils are gray-humus soils with leached off or deeply lying carbonates and with the newly formed Bt horizons in place of the former Bk horizons.

(5) The thickness of the humus layer in the buried soils is often smaller than the depth of the lower boundary of the SHH. This is due to the transfer of humus–clay material from the upper part of the initial A horizon to its lower part, as well as to the fact that, in comparison with the buried soils that stopped their development after burial, the background soils in the past continued to develop as chernozems with an increase in their thickness for some time.

Thus, data summarized in Tables 1 and 2 make it possible to compare the SHH and the buried soils, which could serve as the prototype of the SHH.

Of particular importance are the mounds located in the foothills of the North Caucasus near the settlement of Novosovobodnaya [3, 4]. They are located at 500–700 m a.s.l. Large burial mounds of this site are up to 10 m in height. According to ^{14}C dating, their age is in the interval of 5600–5200 cal. BP[2] [45]. Modern vegetation is represented by oak–beech forests, and background surface soils are gray soils with a strong textural differentiation of the profile. Under the kurgans, there are chernozems with an average thickness of 80 cm and with a well-preserved carbonate horizon and krotovinas. The dates were obtained for the entire profile of the buried chernozems: 6050 ± 170 to 9785 ± 580 (IGAN-1946, 1154). In the background gray soils, the SHH of varying degree of preservation is present at a depth of 60–100 cm. The dates for the humus matter of the SHH correspond to those in the lower part of the buried chernozem, but with signs of some rejuvenation: 7130 ± 40, 7620 ± 150 (IGAN-1084, 2409). Not far from this site, at the Bogatyrskaya Polyana site, clay-illuvial chernozem was studied under the rampart of the fortified settlement. This soil was buried about 2300 yr ago. In that period, the chernozem was at the beginning of the degradation stage and already had a thin eluvial (E) horizon. Lower, within the foothill plain (<200 m a.s.l.), at the transition from forest to the forest-steppe zone (Maikop and Kuzhora sites), the humus horizon of the original chernozems as even thicker than that at the Novosvobodnaya site; the degradation of these chernozems under the forest began later. Therefore, in the background surface dark gray soils, the eluvial part of the profile is thinner (30 cm), while the SHH is thicker and reaches a depth of 130–150 cm.

To the east, in the central part of the North Caucasus, buried chernozems under several kurgans were studied at the Urvan and Chikola sites. The pattern of soil evolution at these sites was the same, but the climate was more continental and arid; therefore, the thickness of chernozems and the depth of the SHH are reduced.

Similar chernozems were found in the CisCarpathian region under kurgans of the Bronze Age (Sarniki, Dashava, modern beech forests), while under the ramparts of the Early Iron Age settlement (Nizhnii Strutin, etc.), gray soils with well-developed bleached E horizons were described. In this area, under the conditions of the forest zone, the change from chernozems to texturally differentiated soils took place about 4000 yr ago [3]. Further to the south, in the forest-steppe zone (the Okopy site in the Dniester River valley), chernozems was buried under the rampart (Troyan Val) in the Early Iron Age, 2350 yr ago, i.e., almost 2000 years later. In the background gray soils, a well-developed SHH (35–85 cm) and krotovinas similar to those in the buried chernozem were found.

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[2] The age of objects and stages of pedogenesis is given in calibrated (calendar) scale. Calibration was performed according to IntCal20 scale [95] with the use of OxCal 4.2 program [75]. Radiocarbon dates of humus reported in the text are given in noncalibrated radiocarbon time scale.

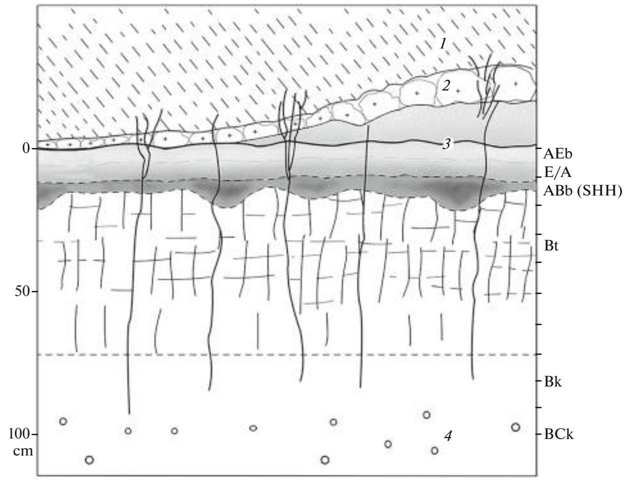

Fig. 3. Gray soil with SHH buried under kurgan of the Bronze Age ca. 4000 yr ago (Mari-El, Prokop'evo site, southern taiga): (*1*) rampart composed of the material of soil horizons of gray, dark gray, and brown colors; (*2*) brown loam ejected from the burial pit; in the left part, it marks the paleosol surface; (*3*) surface of the buried soil; and (*4*) calcareous nodules.

Several kurgans with dark-colored buried paleosols were studied in the area of modern soddy-podzolic and gray soils with the SHH in the Middle Volga reaches, in Chuvashia and Mari-El republics [3]. At the Atlikasy site, kurgan of the Bronze Age is located in the area of gray soils, the SHH lies at a depth of 20–40 (60) cm. Under it, a buried clay-illuvial (podzolized) chernozem (Phaeozem) with the dark-humus horizon of 60 cm was described; carbonates were found from a depth of 75 cm. Three kurgans were studied in the area of soddy-podzolic soils. Under these kurgans, soils with the SHH and with relatively shallow carbonate horizons were described. At the Vilovatovo site, these soils were classified as dark gray soils. The SHH (15–43 cm) was found within the AE horizon and was marked by dark color and good degree of preservation. At the Aleevo and Prokop'evo sites, light gray soils were buried. They had a light-colored AE horizon and a dark-colored SHH (7–23 cm). The soils buried about 2000 years ago, as well as background surface soils, were classified as soddy-podzolic soils (Retisols).

The presence of the SHH in the paleosols buried about 4000 years ago attests to the complicated history of pedogenesis in the Early and Middle Holocene. By the time of construction of the kurgans, the original dark-colored soils had already been subjected to a long stage of textural differentiation and degradation of the dark-colored horizons. However, shortly before the construction of the kurgans, there was probably a short period of climate aridization, during which high-lying carbonate horizons were formed, but dark humus horizons did not have time to appear. Presumably, it was the sharp drying of the climate about 4500–4200 years ago, when "kurgan cultures| of the Bronze Age penetrated far into the modern forest zone. The earlier stages of soil evolution, which took place during the Early and Middle Holocene, were caused by the gradual advance of the forest onto the steppe, which had an oscillatory character.

The SHH date obtained for the Vilovatovo paleosol (8190 ± 90, IGAN-602) shows that the development

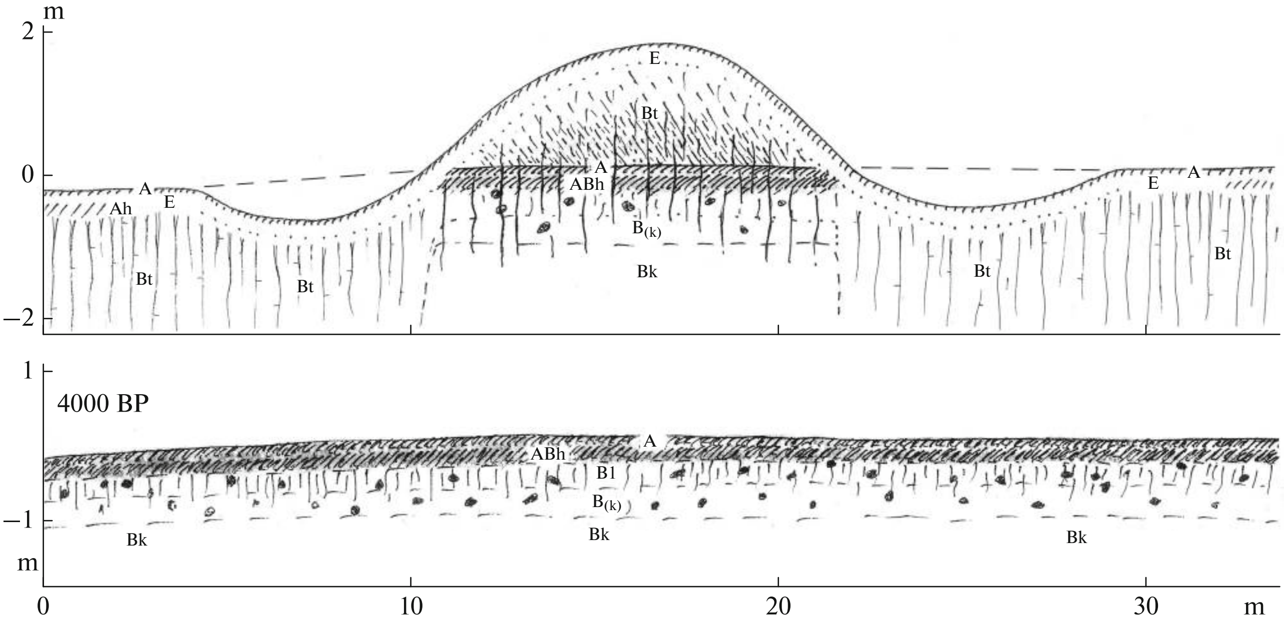

Fig. 4. Dark gray soil with SHH buried under a kurgan about 4000 yr ago, (Vilovatovo site, Mari-El; broadleaved forest).

of the initial dark-colored horizons took place in the Early Holocene, and the beginning of their formation is probably older. In the Early Holocene, the continentality of the climate, characteristic of the Late Glacial period, was still preserved [42]. Therefore, the soils (chernozems) were then thin and, obviously, rich in humus, which is typical of chernozems in continental regions, e.g., in the TransUral region [63].

Low thickness was also characteristic of the Allerød soils that formed under the conditions of a continental climate. In Yaroslavl region (Tekhanovo), the Allerød soil lies below the SHH and is 10 300 ± 60 BP (IGAN-215; 80–90 cm) [2], and this date is somewhat rejuvenated. In the same area, at the Maksimovitsy key site, the Allerød soil also underlies the SHH, and its radiocarbon age may be more rejuvenated (9810 ± 160 BP, IGAN-1231) [66], because this soil lies closer to the surface (60–70 cm). Allerød soils have also been studied in Vologda oblast (Tot'ma, 11 020 ± 240 BP, IGAN-373) [28], in Moscow (Tushino, 11 780 ± 290 BP, IGAN-2319 and 11 260 ± 300, Ki-10562). In their profiles, there are no signs of textural differentiation; humus horizons are thin, black, and are characterized by a somewhat heavier texture in the suprapermafrost (?) horizon. These soils are distinguished by the high resistance of humus to degradation. Possibly, they are included in the composition of some of the most ancient soils with the SHHs in the northern part of their range. In some places, one can see how the Allerød soils rise up the catena and merge with the Holocene SHH 2, Fig. 5].

Soils with the SHH and buried chernozems were also found in the alluvium of floodplains and low terraces of the rivers of the East European Plain. Paleochernozem in the Sadgora section (Khotinsk Elevation) lies at a depth of 2 m in the alluvium of a 10-m terrace of a small left tributary of the Prut River. Humic acids from this soil were dated at 7580 ± 95 (IGAN-1217). During the last 5000 years, a light gray soil (Luvisol) with pronounced E and Bt horizons has been formed on the terrace [3].

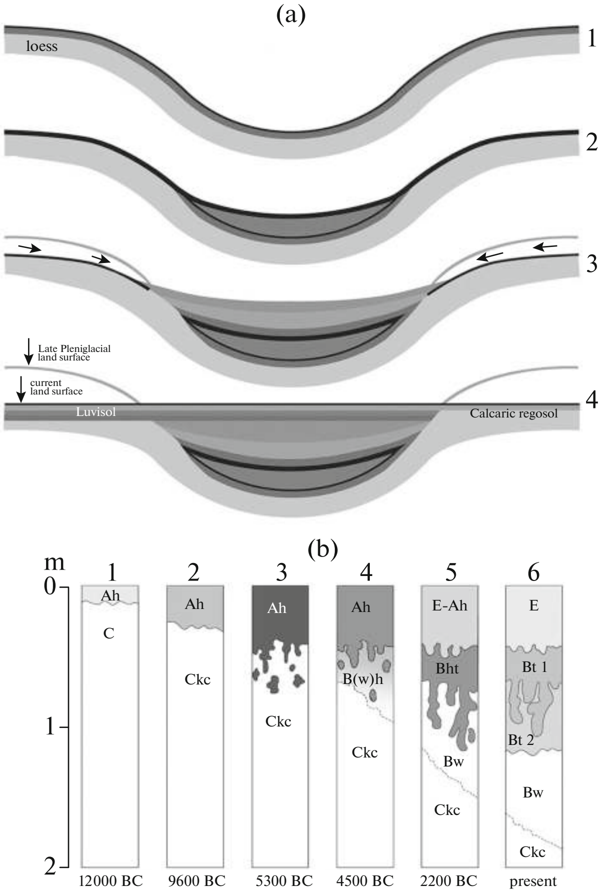

Fig 5. Paleosols on the territory of Germany: (a) stages of formation of Holocene chernozems in hollows according to [88]: 1—Cambisols on loess, 2—Early to Middle Holocene development of Chernozems up to 4700 BP with the participation of colluvial processes; 3—Middle Holocene, erosional processes; and 4—Late Holocene, erosional processes, formation of Luvisols, appearance of arable horizon; (b) evolution of Chernozem into Luvisol with SHH on the territory of Germany according to [90, 97]: 1—loess, initial soil; 2—Regosol, 3—Chernozem, 4—Cambic Chernozem, 5—Luvic Chernozem, and 6—Luvisol.

Buried chernozem and texturally differentiated soils found in the Ranis 2 section of the high ancient floodplain of the Moskva River have been studied in sufficient detail [67, 68]. The profile of the chernozem is thick, with a carbonate horizon and with large krotovinas (passages of hamsters as determined by D. Ponomarenko). Chernozem was formed in the first half of the Holocene, when the floodplain was not flooded and existed as a terrace above the floodplain. A large number of radiocarbon dates were obtained for the chernozem profile: 5570 ± 50 (GIN-15105), 7810 ± 100 (Ki-18753), and 8341 ± 34 (UOC-3109). Calibrated dates for the underlying and overlying sediments make it possible to attribute the time of formation of the chernozem to 5300–10 500 cal. BP. Chernozems and dark-humus soils (Phaeozems) of other sections of the floodplain are of a similar age. Above the column, in the floodplain of the Moskva and Oka rivers, there are soddy-podzolic and gray soils, the main stage of the formation of which dates back to 2500–800 BP. [68]. Also, in the floodplain of the Moskva River, a soddy-podzolic soil with the SHH was found; the SHH was dated at 6640 ± 330 and 6680 ± 80 BP (Ki-17147, Ki-19488 SHV) [67]. It began to form in the early Holocene and passed through the chernozemic stage, which, in addition to the SHH, is evidenced by paleokrotovinas.

SOIL ANALOGUS WITH THE SHH OUTSIDE RUSSIA

The paleosol method proved to be successful in the study of the analogous problem of the origin of Holocene Chernozems in Central Europe [78, 89]. In this region, within the modern forest areas with forest soils, Chernozems and similar dark humus soils were found under the Bronze Age and Neolithic kurgans [70, 78, 83, 86, 87]. They were also found under a Middle Holocene tell in Central Germany [91]. Buried soils were identified as chernozems [86] or similar to them soils (Chernic Phaeozem [87]). The distribution of chernozems in the Middle Holocene (Neolithic) in Central Europe is inconsistent with the Blytt–Sernander climatic scheme. Therefore, some authors attribute their formation to the Subboreal period [84]. However, according to the radiocarbon dating, such chernozems were formed during a long time in the Early and Middle Holocene [86].

The widespread occurrence of steppes in the past in this region is evidenced not only by the soils of the mounds, but also by the soils of the depressions (Fig. 5a). These soils were identified as chernozems that developed from the beginning of the Holocene to about 4700 BP [88].

In Central Europe, the hypothesis of anthropogenic origin of chernozems is being discussed. In this case, the dark color of the soil is associated with the burning of woody vegetation and the accumulation of black carbon due to the washing of particles of dispersed charcoal [81]. However, special studies have shown that dispersed charcoal originated not from woody vegetation but from herbs [88]. According to palynological data, the steppe (*Artemisia*, etc.) then dominated and this stage lasted up to 4000 BP [72]. Thus, a similar Middle Holocene stage of the development of steppe communities and chernozems has been found for Central and Eastern Europe according to the results of multiple paleosol studies [3, 88].

In North America, there are also signs of the earlier (8–4 ka ago) distribution of chernozems [50, 96, 99] that was replaced by the advance of forest communities and forest pedogenesis onto the former steppe areas [6, 71, 73, 77].

In the literature on Central and Western Europe, as well as North America, the presence of SHH in the modern background soils is not mentioned, but there are similar ideas on the patterns of soil evolution as evidenced, for example, by figures from [97] given in [90]. There, the diagrams of the evolution of the soil profile show the transformation of Chernozem into the soil with eluvial (E) and relict residual-humus horizon (Bht, Fig. 5b). Indications of the presence of SHHs in gray soils (Luvisols) are present in the illustrations [84], but they have not been analyzed. Considering this problem in the 1980s, Karavaeva with coauthors noted that the changes in the environmental conditions that created the SHH were quite common in the forest regions of the temperate zone. Organo-accumulative phenomena corresponding to these environmental changes were described many times, especially in West European literature. However, the term “second humus horizon” was never used for them, which ruled out parallels with similar pedogenetic phenomena studied in the Soviet Union [29, p. 172–173].

STAGES OF SOIL EVOLUTION, AGE OF THE SHH, AND ITS REGIONAL DIFFERENCES

Initially, two main stages were distinguished in the development of soils with the SHH: the formation of dark-colored horizons under steppe or meadow vegetation and their degradation under forest vegetation [16, 64, 65]. The transitional stage of Yakovlev’s paramorphosis, characterized by the appearance of vertic features in the chernozems is characteristic of the soils of the Northwest Caucasus, where clayey parent rocks with a high content of smectite are widespread. However, this stage is intermediate; it can be considered a transitional stage to the major stage of the degradation of the initial humus horizon and the development of gray soils.

In some cases, three stages were distinguished for northern SHHs: dark-colored, located between two stages of formation of eluvial horizons [54, 55]. In the opinion of most researchers, including us, the development of the bleached eluvial horizon, which completely encompassed the SHH occurred after the stage of dark-colored pedogenesis [3, 11, 12, 23–25, 60, 65]. In particular, this is evidenced by the study of pairs of buried and background soils, in which signs of a developed E horizon appear only in the Late Holocene. All this testifies to the extremely high stability of the SHH, which has the initial Ca-humus composition and is represented in thin sections by black microclots of stable OM [12, 30].

The study of paleosols with dark-colored humus horizons makes it possible to more definitely represent the geography of the SHH and its prototype. From the south and southwest to the north within the forest zone, the depth of the SHH decreases from 60–80 cm (gray soils) to 30–40 cm in soddy-podzolic soils (subtaiga–broadleaved forests) and 20–25 cm in podzolic soils (middle and southern taiga). Accordingly, the transition from the dark-colored stage to the degradation stage took place from 8 to 4 cal. ka BP. In the forest-steppe, degradation of the dark-humus horizon started only 1–2 ka BP, and the SHH depth is in the range from 40–60 cm in the west to 130–150 cm in the North Caucasus.. In general, a gradual increase in the thickness and depth of occurrence of the SHH to the south is noted, with a maximum in the forest-steppe; these values decrease when moving towards the east, and only in the eastern part of Western Siberia, where the amount of precipitation increases again, the thickness and depth of the SHH also slightly increase.

The onset of the SHH formation can be attributed to the Early Holocene or Allerød (11 or 14 cal. ka BP). In the north of the range, dark-humus soils of the

Allerød (14–13 cal. ka BP) with a considerable clay content could become the part of the SHH in the Holocene because of the exceptional stability of their organic matter. Within the main part of the SHH range (southern taiga–subtaiga) and in the North Caucasus, this transition occurred later, about 4000 BP. This time corresponds to the beginning of the "upper maximum of spruce", which took place after a sharp short drying of the climate 4500–4200 BP. [58]. In the southern regions of the forest-steppe, this transition took place in the first centuries AD, or even at the beginning of the Little Ice Age [3, 61]. In this regard, the chernozemic stage of pedogenesis was the longest in this zone, and the SHH is the youngest, so that it is characterized by a good degree of preservation [17, 60].

The close dependence of the distribution, thickness, and depth of SHHs (and associated paleochernozems) on the environmental conditions fully corresponds to the hypothesis of their residual paleoclimatogenic origin. On the contrary, during sedimentation or turbation burial of horizons, the depth of their occurrence, stratigraphic position, and age are arbitrary, and their distribution is local. In some cases, such locally buried horizons may be similar to paleoclimatogenic horizons. At the same time, to prove the burial of such horizons, geomorphic evidence is needed. In each particular case, it is necessary to establish the sources of the material, and the nature of the processes of its movement and deposition. It is even more difficult to explain all the SHHs by burial [36, 49]. A mantle-like accumulation of material over large areas in the Holocene, and this is how the SHHs are dated, is unlikely. To substantiate the possibility of such accumulation, it is necessary to find the processes leading to the formation of such mantles, as well as sources of material input in such gigantic volumes. When soils are buried under a sediment mantle across large areas, peat bogs and rocks of a different composition should also be buried, which has not been observed.

The turbational SHHs identified in [28] have a certain resemblance to the buried SHHs. It should be noted that the origin of specific humus horizons found at different depths in the form of mottles, lenses, and sloping interlayers in the profiles of Retisols and Luvisols and. often, containing charcoal, has become more evident because of the attention to windfalls and uprooting phenomena. Such horizons are obviously associated with phytoturbation by falling trees; they may be found at a depth of up to 1 m and more and should not be attributed to the SHH. For example, horizons lying at a depth of 6 to 80 cm in the northern part of the SHH area should be referred to as "windfall" horizons [28]. These formations can be considered as both buried and turbated.

Soil evolution patterns were complicated in the south of the area of SHHs. In some cases, paleochernozems display the features of the lower part of the Bt horizon under the layer penetrated by krotovinas. This horizon may be the relic of the short-term stage of forest pedogenesis at the boundary of the Pleistocene and Holocene [3]. Apparently, in addition to the two main stages (Middle and Late Holocene), there were a number of additional stages associated with short-period fluctuations in bioclimatic conditions during the Holocene, including the forest stage at the very beginning of the Holocene. In the evolution of soils with SHHs, such stages are clearly manifested during the Middle Holocene. The stage of brief climate aridization at about 4500 cal. BP is distinguished; it was replaced by the cooling and humidization of the climate about 4000 cal. BP, the next aridization 2000 BP, and the cooling of the Little Ice Age. Cyclic patterns of the formation of peat bogs and SHHs in the center of European Russia could be associated with such climate changes [66]. Analogous conclusions about the directional oscillatory increase in the thickness of chernozems in the Holocene was made in [21].

The study of soils with the SHH is extremely important for elucidating general questions of the evolution of pedogenesis and paleogeography of the temperate zone in the Holocene. The results of the study of SHHs, paleochernozems, and other paleosols indicate considerable changes in the Holocene pedogenesis. At present, there are significant contradictions in the reconstructions of the evolution of pedogenesis in the Holocene, for example, from the complete denial of changes in pedogenesis and the environment to the unambiguous following the Blytt–Sernander scheme of climatic periods [36, 63]. Data on soils with the SHH and on paleochernozems allow us to conclude that the transition from forest to steppe—the main ecotone of the temperate zone—has been the area of contrasting changes in the direction of pedogenesis in the Holocene, and these changes have not followed the Blytt–Sernander scheme. In fact, they proceeded according to the Gerasimov–Markov scheme [9]. This scheme is proved by the presence of paleochernozems in the forest zone, which attests to aridization of the climate in the forest zone and more northern position of the forest/steppe boundary in the Middle Holocene [1, 3, 43, 60, 88, 96]. There are data on paleoclimatology, palynology, and paleogeography showing similar changes in the environment in the Holocene [5, 48, 58, 73]. The evolution of these soils was spatially heterogeneous. In the areas with weakened drainage, hydromorphic soils could evolve into peat-podzolic and mucky-podzolic soils in the Late Holocene because of the humidization and cooling of the climate; such soils could also retain their SHHs. It seems interesting and important to study such variants of the evolution of soils with SHHs. In order to solve the problem, it is necessary to expand the methodological approaches, including modern methods for organic matter studies, micromorphology, and methods of related sciences.

DEGRADATION OF THE SHH AND HUMUS STABILITY OF THIS HORIZON

In the studied SHHs, the destruction of organic matter is facilitated by many processes characteristic of the upper part of the profile (acid hydrolysis, microbial activity, etc.). With an increase in hydromorphism, the activity of microorganisms and the destruction of OM associated with it become weaker, so the SHH is better manifested in the profiles. However, with a further increase in hydromorphism, iron is reduced, becomes mobile, and iron–humus complexes are destroyed, which leads to the removal of both iron and dark-colored organic matter from the SHH [3].

At the same time, SHH is stable, which is associated with its initial properties. The materials of the study of buried soils and the SHH proper attest to an increased stability of the humus of chernozems, which is due to the stability of humate-Ca compounds. These horizons can persist for thousands, tens of thousand, and hundreds of thousand years. On the contrary, the humus horizons of soddy-podzolic, gray and other forest soils are unstable and often significantly degrade already in hundreds of years after their burial Phyto-, zoo- and other turbations, as well as modern plowing, are especially destructive for thin SHHs in the northern part of their area [41].

It is impossible to exclude the existence of other variants of SHHs of a degrading nature, but not classical ones associated with climate changes at the forest-steppe border and degradation of mull humus horizons. Other variants may include degradation of humus horizons of initially hydromorphic soils upon their drainage, or degradation of the thick human-created fertile soil layer upon improper soil management. Undoubtedly, such SHHs will have different ages and be encountered as local phenomena. It is likely that horizons similar to the SHH can be formed during eluvial degradation not only under acidic but also under alkaline conditions. For example, in solonetzic chestnut soils and solonetzes, dark-colored solonetzic horizons are often found under the light-colored eluvial horizons. Such dark-colored solonetzic horizons resemble SHHs in the forest soils. Is this possible in soils with eluvial horizons in other natural zones (tropical?)? At this stage, we can only hypothesize.

At present, the interest in the study of soils with SHH in Russia has somewhat decreased. It is necessary to expand the methods for studying the organic matter of SHHs and to apply the methods of related sciences. In Central Europe and North America, soils with SHHs are also present, but this term is not used for them, and the SHH phenomenon remains unstudied. At the same time, studies of the problem of the origin of the Middle Holocene paleochernozems are being actively pursued. In our opinion, the combination of these two types of objects and the corresponding research directions can lead to a more definite solution to the problem of the development of soils with the SHH.

CONCLUSIONS

Within the forest zone of the temperate zone, there are clearly manifested signs of soil evolution: SHHs and buried chernozems. Soils with the SHH are widespread in the southern taiga–broadleaved forest zones and in the forest-steppe zone on loamy and clayey sediments. Their area stretches along the central zone of the East European Plain and West Siberian Lowland, as well as along the foothills of the North Caucasus. The specific nature of the SHH is due to the presence of humic substances with an extremely high resistance towards degradation, which allows them to remain in the aggressive environment of the eluvial horizons of soddy-podzolic and gray soils. The humate-calcium compounds of the organic matter of chernozems are similarly stable. Under the influence of biochemical and mechanical (tree uprooting) factors, SHHs become strongly transformed, which complicates their study.

Chernozems and dark-colored soils buried under kurgans and ramparts are found in the SHH area. They make it possible to infer the initial state (prototype) of soils with the SHH and the evolutionary paths of the original soils at the stage of their degradation.

Soils with the SHH and paleochernozems are widespread in the forest zone, which attests to contrasting changes in pedogenesis and bioclimatic conditions in the Holocene. The advance of the forest over the steppe was caused by an increase in climate humidity and began in Early Holocene; it was not a unidirectional process; there were certain fluctuations. The maximum advance of forests took place during the Little Ice Age. Attempts to assign the SHH and paleochernozems exclusively to the Subboreal period of the Holocene have not been supported by factual evidence. Radiocarbon dates for the initial period of the formation of these soils range within 4–9 ka BP; in the forest-steppe zone, the stage of dark-humus pedogenesis continued longer, up to 1–2 ka ago BP.

In accordance with climate and biota conditions, the thickness of the SHH and its prototype in the northern part of the range (middle–southern taiga) is minimal (20–30 cm) and increases to the south and west (60–80 cm); the maximum thickness of the SHH is in the forest-steppe of the North Caucasus (130–150 cm). The transition from the dark-colored stage to the degradation stage was the earliest in the north of the range (about 8 ka BP) and the latest in the forest-steppe (2–1 ka BP).

Residual paleoclimatogenic SHHs reflect the state of the past soil cover, which in most of the SHH range belongs to the Middle Holocene, and is represented by more eutrophic soil variants. In the modern soil cover, in addition to the preserved elements of this relict soil cover, hydromorphic, buried, and lithological formations with a complicated organoprofile are locally embedded [23, 26, 28, 31, 40, 43].

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. I. G. Avenarius, M. V. Muratova, and I. I. Spasskaya, *Paleogeography of the Northern Eurasia in the Late Pleistocene–Holocene and Geographical Forecast* (Nauka, Moscow, 1978) [in Russian].
2. A. L. Alexandrovskiy, *Holocene Evolution of Soils on the East European Plain* (Nauka, Moscow, 1983) [in Russian].
3. A. L. Alexandrovskiy and E. I. Aleksandrovskaya, *Evolution of Soils and the Environment* (Nauka, Moscow, 2005) [in Russian].
4. A. L. Alexandrovskiy and A. G. Birina, "Evolution of gray forest soils in the foothills of the North Caucasus," Pochvovedenie, No. 8, 28–39 (1987).
5. I. I. Borzenkova, *Climate Dynamics in Cainozoic* (Gidrometeoizdat, St. Petersburg, 1992) [in Russian].
6. S. W. Buol, F. D. Hole, and R. J. McCracken, *Soil Genesis and Classification* (Iowa State University Press, Ames, IA, 1973; Progress, Moscow, 1977).
7. D. A. Gavrilov, "The genesis of the second humus horizon in soils of the Vasyugan sloping plain," Byull. Pochv. Inst. im. V.V. Dokuchaeva, No. 85, 3–19 (2016). https://doi.org/10.19047/0136-1694-2016-85-5-19
8. I. M. Gadzhiev, *Evolution of Southern Taiga Soils in Western Siberia* (Nauka, Novosibirsk, 1982) [in Russian].
9. I. P. Gerasimov and K. K. Markov, *Glacial Period in the Soviet Union* (Academy of Sciences of the USSR, Moscow, 1939) [in Russian].
10. A. A. Gol'eva and A. L. Aleksandrovskii, "The application of phytolith analysis for solving problems of soil genesis and evolution," Eurasian Soil Sci. **32**, 884–891 (1999).
11. G. V. Dobrovol'skii, T. V. Afanas'eva, V. I. Vasilenko, and G. L. Remezova, "Genesis and geography of soils in Tomsk Ob' region," Pochvovedenie, No. 10, 3–12 (1969).
12. G. V. Dobrovol'skii, T. V. Afanas'eva, K. N. Fedorov, and S. A. Shoba, "Micromorphology and genesis of secondary-podzolic soils of Western Siberia," Pochvovedenie, No. 12, 60–70 (1972).
13. G. V. Dobrovol'skii and I. S. Urusevskaya, *Geography of Soils* (Moscow State Univ., Moscow, 1984) [in Russian].
14. V. V. Dokuchaev, "Ratio between age and local altitude and character and distribution of chernozems, forest soils, and solonchaks," Vestn. Estestvozn., Nos. 1–3, 18–29 (1891).
15. V. V. Dokuchaev, *Russian Chernozem: A Report for Imperial Free Economic Society* (Imperial Free Economic Society, St. Petersburg, 1883) [in Russian].
16. D. A. Dranitsyn, "Secondary podzols and shift of podzolic zone in the north of the Ob–Irtush interfluve" Izv. Dokuchaevskogo Pochv. Kom., No. 2, 31–93 (1914).
17. A. G. Dyukarev and N. N. Pologova, "Nature of second humus horizons in soils of Western Siberia," in *Proceedings of the VI All-Russian Conf. with International Participation Dedicated to the 125 Anniversary of R. S. Il'in "Reflection of Bio-, Geo-, and Anthropospheric Interactions in Soils and Soil Cover"* (Tomsk, 2016), pp. 162–165.
18. Ph. Duchaufour, *Pédologie* (École Nationale des Eaux et Forêts, Nancy, 1956); Ph. Duchaufour, *L'Évolution des sols: Essai sur la Dynamique des Profils* (Masson et Cie, Paris, 1968).
19. S. A. Zakharov, "Competition between forest and steppe in the Caucasus," Pochvovedenie, No. 3–4, 500–545 (1935).
20. V. P. Zolotun, "The origin of loess deposits in the south of Ukraine," Pochvovedenie, No. 1, 29–38 (1974).
21. V. P. Zolotun, Doctoral Dissertation in Agriculture (Kiev, 1974).
22. I. V. Ivanov and A. L. Alexandrovskiy, *Study Methods of Evolution and Age of Soils* (Pushchino, 1984) [in Russian].
23. E. N. Ivanova and P. A. Dvinskikh, "Secondary-podzolic soils of the Urals," Pochvovedenie, No. 7–8, 325–344 (1944).
24. R. S. Il'in, "On soil degradation and secondary-podzolic soils of Siberia," Pochvovedenie, No. 4, 591–600 (1937).
25. N. A. Karavaeva, "Genesis and evolution of the second humus horizon in the soils of the southern taiga of Western Siberia," in *Pedogenesis and Weathering in Humid Landscapes* (Nauka, Moscow, 1978), pp. 133–157.
26. N. A. Karavaeva, "Current waterlogging in soils of the southern taiga of Western Siberia and evolution of the soil cover in the Holocene," in *Pedogenesis and Weathering in Humid Landscapes* (Nauka, Moscow, 1978), pp. 158–210.
27. N. A. Karavaeva and E. N. Subbotina, "Humus composition in soddy-podzolic soil with secondary humus horizon," Pochvovedenie, No. **7**, 23–33 (1977).
28. N. A. Karavaeva, A. E. Cherkinskii, and S. V. Goryachkin, "The second humus horizon and the evolution of podzolic loamy soils of the Russian Plain," in

Evolution and Age of Soils of the USSR (Pushchino, 1986), pp. 120–138.

29. N. A. Karavaeva, A. E. Cherkinskii, and S. V. Goryachkin, "The concept of "second humus horizon": genetic-evolutionary systematization," in *Advances of Soviet Soil Science* (Nauka, Moscow, 1986), pp. 167–173.
30. D. V. Karpova, P. N. Balabko, N. P. Chizhikova, L. V. Beskin, N. A. Kolobova, T. I. Khusnetdinov, P. R. Tsymbarovich, and M. V. Belyaeva, "Micromorphology and mineralogy of gray forest soils of the Vladimir opolie," Byull. Pochv. Inst. im. V.V. Dokuchaeva, No. 94, 101–123 (2018). https://doi.org/10.19047/0136-1694-2018-94-101-123
31. P. P. Kerzum, A. V. Rusakov, and N. N. Matinyan, "Geomorphic position of paleosols and the soil cover of the center of the Russian Plain in the Holocene," Pochvovedenie, No. 11, 28–35 (1989).
32. L. L. Shishov, V. D. Tonkonogov, I. I. Lebedeva, and M. I. Gerasimova, *Classification and Diagnostic System of Russian Soils* (Oikumena, Smolensk, 2004) [in Russian].
33. S. I. Korzhinskii, "The northern border of the chernozem-steppe region in the eastern part of European Russia in botanical and soil terms," Tr. O-va Estestvoispyt. Kazan. Univ. **22** (6), (1891).
34. P. S. Kossovich, *Fundamentals of Soil Theory* (St. Petersburg, 1911), Part 2, No. 1.
35. I. I. Lebedev and V. D. Tonkonogov, "Reflection of the evolution of landscapes in the texturally differentiated soils of northern Eurasia," in *Proceedings of the IV All-Russian Conf. "Soil Evolution"* (Pushchino, 2003), pp. 11–17.
36. A. O. Makeev, *Surface Paleosols of Loess Watersheds of the Russian Plain* (Molnet, Moscow, 2012) [in Russian].
37. S. N. Nikitin, "Chernozem of Vladimir region," Izv. Geol. Kom. **4**, 98–111 (1885).
38. L. D. Nikiforova, Candidate's Dissertation in Geography (Moscow, 1980).
39. V. A. Nikolaev, "Paragenesis of woodland–opolie in central Russia," Vestn. Mosk. Univ., Ser. 5: Geogr., No. 5, 45–50 (2013).
40. B. F. Petrov, "Origin of the second humus horizon in podzolic soils of Western Siberia," Tr. Tomsk. Univ. **92**, 43–69 (1937).
41. A. M. Prokashev, "Holocene evolution and anthropogenic transformation of the soil cover of the Vyatka Kama region," in *Evolution of Soils and Soil Cover: Theory, Diversity of Natural Evolution and Anthropogenic Transformations* (GEOS, Moscow, 2015), Ch. 14.2, pp. 401–421.
42. A. M. Prokashev, *Soils with Complex Organic Profile of the South of Kirov Oblast: Ecology, Properties, and Genesis* (Vyatka State Pedagogical Univ., Kirov, 1999) [in Russian].
43. A. M. Prokashev, I. A. Zhuikova, and M. M. Pakhomov, *History of Development of Soil-Vegetation Cover in Vyatka-Kama Region in Post Glacial Period* (Vyatka State Pedagogical Univ., Kirov, 2003) [in Russian].
44. A. M. Prokashev, E. S. Soboleva, A. S. Imenitova, I. A. Vartan, A. S. Matushkin, N. D. Okhorzin, S. L. Mokrushin, and I. L. Borodatyi, "Soddy-podzolic soils with a complex organic profile in the right-bank part of the Lower Vyatka River Basin," Eurasian Soil Sci. **51**, 758–771 (2018).
45. A. D. Rezepkin, *Novosvobodnenskaya Culture (Based on Materials from the Klady Burial)* (Nestor-Istoriya, St. Petersburg, 2018) [in Russian].
46. A. A. Rode, *Pedogenesis and Evolution of Soils* (Geografgiz, Moscow, 1947) [in Russian].
47. L. P. Rubtsova, "Differentiation of the humus horizon in gray forest soils," Byull. Pochv. Inst. im. V.V. Dokuchaeva, No. 2, 3–10 (1968).
48. T. A. Serebryanaya, " Dynamics of the boundaries of the Central forest-steppe in the Holocene," in *V.N. Sukachev's Biennial Meeting "Century Dynamics of Biogeocenosises"* (Nauka, Moscow, 1992), pp. 54–71.
49. I.A. Sokolov, "Genesis, diagnostics, and classification of soils with a texture-differentiated profile," Pochvovedenie, No. 11, 32–41 (1988).
50. S. H. Spurr and B. V. Barnes, *Forest Ecology* (Wiley, New York, NY, 1980; Lesnaya Prom-st', Moscow, 1984).
51. S. A. Sycheva, N. B. Leonova, A. L. Alexandrovskiy, et al., *Natural Science Methods of Study of the Cultural Layers of Ancient Settlements* (NIA-Priroda, Moscow, 2004) [in Russian].
52. G. I. Tanfil'ev, "About chernozem in Vladimir region," Tr. Vol'nogo Ekon. O-va, No. 1, 47–53 (1896).
53. V. O. Targulian, "Soil evolution," in *Problems in Soil Science* (Nauka, Moscow, 1982), pp. 108–113.
54. V. V. Tyulin, *Soils of Kirov Oblast* (Volgo-Vyatskoe Knizhn. Izd., Kirov, 1976) [in Russian].
55. V. V. Tyulin and M. V. Rossokina, "Soils with second humus horizon in Chepetsk-Kil'mez watershed," Pochvovedenie, No. 7, 28–37 (1967).
56. A. N. Tyuryukanov and T. A. Bystritskaya, *High Plains of Central Russia and Their Soils* (Nauka, Moscow, 1971) [in Russian].
57. A. A. Khantulev and E. I. Gagarin, "Genesis and geography of soils with complex humus profile," Pochvovedenie, No. 2, 3–13 (1972).
58. N. A. Khotinskii, *Holocene of Northern Eurasia* (Nauka, Moscow, 1977) [in Russian].
59. N. A. Khotinskii, Z. V. Aleshinskaya, M. A. Guman, V. A. Klimanov, and A. E. Cherkinskii, New scheme of periodization of landscape-climatic changes in Holocene," Izv. Ross. Akad. Nauk, Ser. Geogr., No. 3, 30–42 (1991).
60. Yu. G. Chendev, *Evolution of Forest-Steppe Soils of the Central Russian Upland in the Holocene* (GEOS, Moscow, 2008) [in Russian].
61. Yu. G. Chendev, A. L. Aleksandrovskii, O. S. Khokhlova, M. I. Dergacheva, A. N. Petin, A. N. Golotvin,

V. A. Sarapulkin, G. L. Zemtsov, and S. V. Uvarkin, "Evolution of forest pedogenesis in the south of the forest-steppe of the Central Russian Upland in the Late Holocene," Eurasian Soil Sci. **50**, 1–13 (2017).

62. G. V. Sharpensil, "Radiocarbon dating of soils," Pochvovedenie, No. **1**, 34–42 (1971).
63. *Evolution of Soils and Soil Cover: Theory, Diversity of Natural Evolution, and Anthropogenic Transformations of Soils*, Ed. by V. N. Kudeyarov and I. V. Ivanov (GEOS, Moscow, 2015) [in Russian].
64. S. A. Yakovlev, "Degradation of chernozems in the western part of the North Caucasus," Pochvovedenie **16** (4), 1–20 (1914).
65. S. A. Yakovlev, *Soils and Grounds along Armavir-Tuapse Railways* (St. Petersburg, 1914) [in Russian].
66. A. L. Alexandrovskiy, "Soil evolution on the lower terraces of Lake Nero," Eurasian Soil Sci. **44**, 1055–1067 (2011). https://doi.org/10.1134/S106422911100024
67. A. L. Alexandrovskiy, E. G. Ershova, and N. A. Krenke, "Buried Late-Holocene Luvisols of the Oka and Moskva River floodplain and their anthropogenic evolution according to soil and pollen data," Quat. Int. **418**, 37–48 (2016).
68. A. L. Aleksandrovskii, E. G. Ershova, E. V. Ponomarenko, N. A. Krenke, and V. V. Skripkin, "Natural and anthropogenic changes in the soils and environment of the Moskva River floodplain in the Holocene: pedogenic, palynological, and anthropological evidence," Eurasian Soil Sci. **51**, 613–627 (2018).
69. A. L. Alexandrovskiy, S. N. Sedov, V. A. Shishkov, "The development of deep soil processes in ancient kurgans of the North Caucasus," Catena **112**, 65–71 (2014).
70. W. Baumann, C. Fritzsche, W. Coblenz, H. J. Fiedler, and H.-P. Brückner, "Stratigraphische Befunde zur Schnurkeramik in einem Grabhügel bei Werben, Kr. Leipzig," Ausgrabung Funde **28**, 1–10 (1983).
71. E. A. Bettis III, D. W. Benn, and E. R. Hajic, "Landscape evolution, alluvial architecture, environmental history, and the archaeological record of the Upper Missouri Valley," Geomorphology **101**, 362–377 (2008).
72. J. A. Bos, "Late Glacial and Early Holocene vegetation history of the northern Wetterau and the Amöneburger Basin (Hessen), central-west Germany," Rev. Palaeobot. Palynol. **115** (3–4), 177–204 (2001). https://doi.org/10.1016/S0034-6667(01)00069-0
73. R. S. Bradley, *Paleoclimatology: Reconstructing Climates of the Quaternary* (Academic, San Diego, 1999).
74. R. S. Bradley, *Paleoclimatology: Reconstructing Climates of the Quaternary* (Academic, San Diego, 2015).
75. C. Bronk Ramsey, "Bayesian analysis of radiocarbon dates," Radiocarbon **51** (1), 337–360 (2009). https://doi.org/10.1017/S0033822200033865
76. Y. Chendev, A. Aleksandrovskiy, O. Khokhlova, and V. Skripkin, "^{14}C dating to study the development of soils in the forest-steppe of the Central Russian Upland as a result of bioclimatic changes and long-term cultivation," Radiocarbon **60** (4), 1185–1198 (2018). https://doi.org/10.1017/RDC.2018.40
77. Yu. G. Chendev, J. A. Hubbart, E. A. Terekhin, A. R. Lupo, T. J. Sauer, and C. L. Burras, "Recent afforestation in the Iowa River and Vorskla river basins: a comparative trends analysis," Forests **7** (11), (2016). https://doi.org/10.3390/f7110278
78. P. Czerny, "Bodenkundliche untersuchungen an einer fossilen und einer rezenten Schwarzerde," Albrecht-Thaer-Arch. **9** (10), 867–881 (1965).
79. Ph. Duchaufour, *Precis De Pedologie* (Masson et Cie, Paris, 1965).
80. Ph. Duchaufour, *L'Évolution des Sols: Essai sur la Dynamique des Profiles* (Masson et Cie, Paris, 1968).
81. E. Eckmeier, R. Gerlach, E. Gehrt, and M. W. I. Schmidt, "Pedogenesis of chernozems in central Europe—a review," Geoderma **139**, 288–299 (2007).
82. J. Fink, "Die Böden Österreichs," Mitt. Geogr. Ges. Wien **100** (3), 92–134 (1958).
83. M. Hejcman, K. Součková, P. Krištuf, and J. Peška, "What questions can be answered by chemical analysis of recent and paleosols from the Bell Beaker barrow (2500–2200 BC), Central Moravia, Czech Republic?" Quat. Int. **316**, 179–189 (2013).
84. I. Hildebrandt-Radke, P. Makarowicz, Z. N. Matviishyna, A. Parkhomenko, S. D. Lysenko, and I. T. Kochkin, "Late Neolithic and Middle Bronze Age barrows in Bukivna, Western Ukraine as a source to understand soil evolution and its environmental significance," J. Archaeol. Sci. **27**, 101972 (2019). https://doi.org/10.1016/j.jasrep.2019.101972
85. IUSS Working Group WRB, *World Reference Base for Soil Resources 2014, International Soil Classification System for Naming Soils and Creating Legends for Soil Maps, World Soil Resources Reports No. 106* (UN Food and Agriculture Organization, Rome, 2014).
86. C. Kabała, A. Przybył, M. Krupski, B. Łabaz, and J. Waroszewski, "Origin, age and transformation of chernozems in northern Central Europe—New data from Neolithic earthen barrows in SW Poland," Catena **180**, 83–102 (2019). https://doi.org/10.1016/j.catena.2019.04.014
87. M. Krupski, M. Mackiewicz, C. Kabała, M. Ehlert, and M. Cendrowska, "Earthen mounds in the Głubczyce Forest (SW Poland)—are they prehistoric long-barrows? Geoarchaeology of the Silesian soil record and human-environment interplay in the Holocene," Praehist. Z. (2021). https://doi.org/10.1515/pz-2021-0004
88. P. Kuhn, E. Lendorff, and M. Fuchs, "Late glacial Period in the Holocene of soil formation and formation of colluvial deposits in loess landscapes of Central Europe (Wetterau, Germany)," Catena **154**, 118–135 (2017).
89. W. Laatsch, *Dinamik der Mitteleuropaischen Mineralboden* (Dresden, 1957).

90. C. Lorz and T. Saile, “Anthropogenic pedogenesis of Chernozems in Germany?—A critical review,” Quat. Int. **243** (2), 273–279 (2011).
91. C. C. M. Lubos, S. Dreibrodt, V. Robin, O. Nelle, S. Khamnueva, I. Richling, U. Bultmann, and H.-R. Bork, “Settlement and environmental history of a multilayered settlement mound in Niederröblingen (central Germany)—a multi-proxy approach,” J. Archaeol. Sci. **40** (1), 79–98 (2013).
92. E. A. Paul, C. A. Campbell, D. A. Rennie, and D. J. McKallum, “Investigation of the dynamics of soil humus utilizing carbon dating techniques,” in *Proceedings of the 8th Int. Congr. on Soil Science* (Bucharest, 1964), Vol. 3, pp. 201–208.
93. D. Pietsch, P. Kühn, S. Lisitsyn, A. Markova, and A. Sinitsyn, “Krotovinas, pedogenetic processes and stratigraphic ambiguities of the Upper Palaeolithic sites Kostenki and Borshchevo (Russia),” Quat. Int. **324**, 172–179 (2014).
94. D. Ponomarenko and E. Ponomarenko, Describing krotovinas: a contribution to methodology and interpretation,” Quat. Int. **502**, 238–245 (2019).
95. P. Reimer, W. Austin, E. Bard, A. Bayliss, P. Blackwell, C. Bronk Ramsey, M. Butzin, et al., “The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP),” Radiocarbon **62** (4), 725–757 (2020). https://doi.org/10.1017/RDC.2020.41
96. R. V. Ruhe and W. H. Scholtes, “Ages and development of soil landscapes in relation to climatic and vegetational changes in Iowa,” Soil Sci. Soc. Am. J. **20** (2), 264–273 (1956).
97. J. Schalich, “Boden- und Landschaftsgeschichte,” in *Der Bandkeramische Siedlungsplatz Langweiler*, Vol. 8: *Gemeinde Aldenhoven, Kreis Düren (Rheinische Ausgrabungen)* (Rheinland-Verlag, Bonn, 1988), pp. 17–29.
98. H. W. Scharpenseel, “Radiocarbon dating of soils—problems, troubles, hopes,” in *Paleopedology: Origin, Nature, and Dating of Paleosols* (Jerusalem, 1971), pp. 77–88.
99. A. Schwalb and W. E. Dean, “Reconstruction of hydrological changes and response to effective moisture variations from North-Central USA lake sediments,” Quat. Sci. Rev. **21** (12–13), 1541–1554 (2002).
100. H. Stremme, “Die Böden des deutschen Reiches und der freien Stadt Danzig. Miteiner Übersichtskarte, Maßstab 1 : 1000000,” Petermanns Geogr. Mitt. **226**, (1936).
101. H. Stremme, “Grundzüge der Praktischen Bodenkunde,” in *Grundzüge der Praktischen Bodenkunde* (Berlin, 1926).

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