Soil Catenas in Archeological Landscapes

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Abstract—Soil catenas crossing various archeological objects (ramparts, ancient settlements, burial mounds, etc.) with an age of 360–1800 years have been studied in the subzones of dark chestnut soils and typical, ordinary, and southern chernozems in the East European Plain. It is found that topography-induced variations in the thickness of zonal soil types are not always distinct. Often, the thickness of soil profiles does not depend on the slope gradient. In this context, it is supposed that the rate of the formation of humus horizons on slopes exceeds that on leveled surfaces. A comparative analysis of the thickness of humus horizons along soil catenas offers excellent possibilities for the determination of the rates of erosion and pedogenesis. The methodology of quantitative assessment of the potential rate of soil formation on slopes is suggested.

FORMULATION OF THE PROBLEM

In the past few decades, considerable progress has been achieved in the study of soil evolution. At present, we can trace the Holocene history of automorphic (autonomous) zonal soils in the Russian Plain. However, in many places, the normal development of soils is complicated by erosion and redeposition of sediments. In these cases, a routine study of the soil profile morphology should be supplemented with the study of dynamic processes in the landscape [23]. The catenary approach based on the analysis of geochemically conjugated soils seems to be very promising for this purpose.

The concept of soil catena implies the integral analysis of the soil profile and the soil cover (pedological landscape) [12]. Soil catena was defined by Milne [40] as a sequence of soils that develop from similar (as a rule) rocks, but in different topographic positions (summits, slopes, footslopes, etc.). The catenary approach is widely applied in soil science [30, 41–43]. The differentiation of surface runoff along the slope dictates the differences in the rates of soil formation and, hence, the differences in the morphology of soils composing the catena. Gradually, the concept of soil catena has acquired a new meaning. At present, it is applied successfully not only to the description of hydrological processes, but also to the study of the soil cover pattern and its spatial and temporal evolution [15]. Gennadiev [7] suggested the concept of spatial–temporal models of pedogenesis. To develop these models, we should study not separate soils, but soil combinations composing the chronosequence and allocated to different elements of local topography, different kinds of parent rocks, and different vegetation associations, i.e., pedotopocatenas, pedolithocombinations, and pedophytocombinations.

Ecologists and geobotanists consider soil changes on slopes in relation to the changes in the biota. From this point of view, catenas may serve as the objects for combined analysis of soil evolution, plant successions, and the dynamics of animal population [26]. In this context, the concept of polyclimax development can be applied not only to the soils, but also to vegetation. The zonal type of vegetation can be considered a combination of several climax associations of plants differentiated by the elements of microtopography, or a mosaic of topographic, microclimatic, and edaphic vegetation complexes. Regular changes in the character of vegetation along the slope gradient allow us to distinguish corresponding landscape structures that are called landscape strips [24, 29], slope microzones [25], or paragenetic natural complexes [3]. The latter may be integrated into landscape regions characterized by the similarity of changes in natural complexes along slope gradients [23]. In order to reveal the effect of separate factors on the catenary structure of landscapes (and soils), it is reasonable to study such catenas, in which just one of the factors is a variable, whereas all the rest are relatively stable. In macrocatenas, the soils developing at different topographic levels may have different ages [1, 2, 35]; this circumstance complicates the interpretation of the results. Meanwhile, the study of soil catenas crossing various archeological objects (ancient settlements, ramparts, burial mounds, etc.) with a quite definite time of the beginning of soil formation (the zero moment) allows us to reveal the effect of geomorphic conditions (in particular, the slope gradient) on soil development and to trace the history of soil evolution and plant successions along such relatively monochronous catenas.

This aim of this study is to determine out the regularities of morphological changes of soils along the topocatenas of a definite age and to estimate the potential rate of soil formation on the basis of quantitative data on the thickness of soil humus horizons along the slope.

OBJECTS AND METHODS

Six soil catenas allocated to archeological objects of different ages (from 360 to 1800 years) were studied in the subzones of dark chestnut soils and typical, ordinary, and southern chernozems of the East European Plain. The studies were conducted in the territories of the Russian Federation, Ukraine, and Moldova. The zero moments of soil formation within these catenas were established on the basis of archeological and historical data.

(1) Belgorod oblast, Russia. The defense line (abatis) with a total length of nearly 800 km was constructed along the southern border of the Russian State in 1635–1646. A part of this defense line stretching from Belgorod to Bolkhovets and Karpov represents an artificial levee (rampart). The beginning (July 1, 1636) and the end (September 15, 1637) of the construction of this rampart, as well as its original geometric parameters (the length, ca. 13 km; the width in the top, about 6.4 m, and the height about 3.2 m), are known from historical records [14, pp. 75–76]. The rampart was surrounded by a ditch. At present, a part of this rampart (4154 m, or 37.8% of the original length) is preserved not far from the Bolkhovets settlement [31]. We studied the catena from the top of the rampart to the bottom of the ditch surrounding it; the 20.3-m-long trench was excavated. The soils around the rampart (background surface soils) are represented by moderately deep, low-humus typical chernozems.

(2) Vulkunesht district of Moldova and Bolgrad district (Odessa oblast) of Ukraine. The so-called Trajan rampart (126 km) was constructed by Roman soldiers in the beginning of the second century AD to protect the new Roman province of Dacia [11]. We studied a catena across this famous rampart on the right bank of the Bol'shoi Yalpug River. The background soils are represented by shallow-calcareous low-humus ordinary chernozems.

(3) Belgorod–Dniester district, Odessa oblast, Ukraine. The construction of the Zmiev rampart found in this area dates back to the middle of the fourth century AD as evident from the archeological artifacts buried under the rampart and dating back to the ancient settlement that existed in place of the rampart in the second and third centuries AD. A topographic survey conducted in 1870–1877 in this area showed that the rampart stretched from the right bank of the Dniester Liman to the settlement of Akerman (at present, Belgorod-on-Dniester) and had a length of about 12 km. We studied a part of this rampart near the settlement of Sadovoe. The background soils are represented by micellar-calcareous low-humus ordinary chernozems.

(4) Ovidiopol district, Odessa oblast, Ukraine. The settlement of Nikonii was constructed by Byzantine Greeks in this area. The territory of the settlement occupies about 3.8 ha. The settlement was abandoned in the fourth century AD, and the soil formation started on the cultural layer. We studied the soil catena on a gentle slope of southwestern aspect. At present, this is an idle land covered with natural grasses. A relatively short stage of the agricultural development of this land began in 1910. The background soils are represented by loamy low-humus southern chernozems.

(5) Crimea, Ukraine (29 km to the west of the city of Kerch). The Uzunlar or Akkosov rampart (36 km) was constructed in this area. Data on the time of its construction are rather contradictory. In some places, the rampart was reconstructed and new portions of earth were added to it. However, judging from the analysis of the thickness of humus profiles of soils formed within this rampart, we can definitely say that it was constructed in the second century AD [19]. The background soils are represented by moderately deep, low-humus typical chernozems.

(6) Berezan district, Nikolaev oblast, Ukraine. In the southern part of the peninsula that separates the Berezan and Sositsk limans, the defense constructions of the ancient settlement (Mys I) were discovered. These constructions represent a system of a ditch, a rampart, one more ditch, and a stony wall inside. They were created by Romans in the beginning of our era [4, p. 58]. Later, during the reign of Antoninus Pius (138–161 AD), when barbaric tribes destroyed several settlements around the Bug Liman but failed to attack the settlements around the Berezan Liman being stopped by Roman troops, the defense lines were renovated and the ditches were deepened [4, p. 134]. Until the middle of the third century AD, these lines protected the ancient settlement. Later, it was abandoned. The background soils in this region are represented by loamy–clay, dark chestnut soils with residual solonetzic properties.

Along with soil catenas crossing these archeological objects, we also studied several natural catenas: (a) the catena in the Glubokaya gulch (Komintern district, Odessa oblast) with full-profile southern chernozems (Fig. 1); (b) the catena along the southern slope with plowed southern chernozems in the same region (length, 600 m; gradient, 2.5°); (c) the catena in the Ovidiopol district (eastern slope with a gradient of 2.4° and length of 200 m; southern chernozems); and (d) the catena in the Ivanovskii district (Odessa oblast) displaying shallow ordinary chernozems on the slopes of western and eastern aspects with lengths of 630 and 780 m and gradients of 2° and 3°, respectively.

The main method of our study consisted of a very detailed description of soil trenches dug along the catenas in combination with a morphometric analysis of local topography (data of geodetic leveling were used for this purpose) and phytocenotic studies (the species composition of plant associations and the phytomass (dry weight) density were determined). The color of soil horizons was described in the Munsell system (*Munsell Soil Color Charts*, 1975).

While analyzing the susceptibility of separate soil profiles composing the catena to erosional processes, we used averaged values of the relief function $F(L, J)$ substantiated in [37]. This function describes the effect

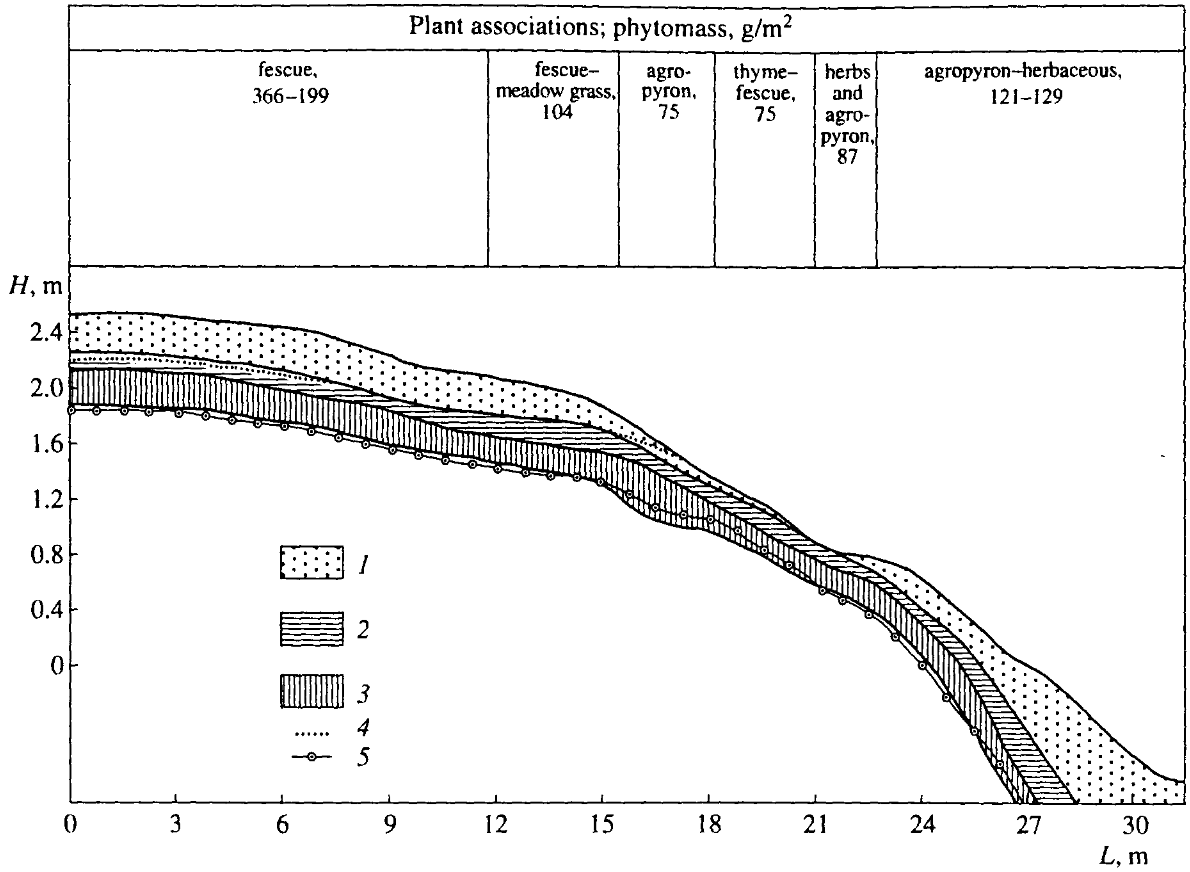

Fig. 1. The catena with full-Holocene southern chernozems; rangeland. Genetic horizons: (*1*) A, (*2*) AB1, (*3*) Bk, (*4*) depth of effervescence, and (*5*) the upper boundary of soft calcareous nodules.

of topography on soil loss tolerance. Adding the correction coefficients for the effect of the aspect and shape of a slope on soil loss tolerance [33], we obtain

$$F(L; J) = X_{ri}J^nL^{0.5}, \qquad (1)$$

where X_{ri} is the coefficient depending on the aspect and shape of a slope; J is the slope gradient, %; L is the slope length, m; and n is the exponent depending on the character of the soil surface.

RESULTS

The study of vegetation patterns along the catenas in combination with data on plant successions on cultural layers of different ages (from 1600 to 3500 years) [22] proved that the vegetation is more responsive to the changes in the environmental factors than the soils. Thus, the above ground phytomass of plants growing over dated surfaces with an age of 2000–3000 years reaches 80–84% of the above ground phytomass of full-Holocene plant associations. At the same time, the thickness of the humus profile of soils with an age of 1600–1800 years reaches just 66% of the thickness of full-Holocene soils; the thickness of soils with an age of 2200–3200 years comprises about 79% of the thickness of full-Holocene soils (at least, in conditions of the steppe zone).

As was found earlier [20], mean annual rates of the development of the humus horizon of soils during the Subatlantic period (the last 2500 years) do not exceed 0.20–0.25 mm for ordinary chernozems, 0.18–0.23 mm for southern chernozems, and 0.15–0.20 mm for dark chestnut soils. However, the decrease in the rate of the development of soil humus horizons from the north (the forest-steppe and typical steppe subzones) to the south (the dry steppe subzone) is especially typical for leveled automorphic positions in soil catenas, i.e., for flat tops. The thickness of the humus profile on slopes is dictated not only by the rate of humus formation, but also by the processes of erosion and redeposition of sediments differentiated by the elements of meso- and microtopography.

The average thickness of the humus horizon in the sloping part of the catena across the Belgorod rampart (length, 14 m; inclination, 9.8°) comprises 16.85 cm, which is approximately equal to the thickness of the humus horizon on the leveled top of the rampart (H = 16.98 ± 1.54 cm; C_V = 5.1%; data from 32 separate measurements).

The morphology of soils formed on the ramparts

Location	Intensity of erosion (or accumulation)	Thickness of horizons, cm		ΔH, mm/year
		A	A + AB	
The Bolkhovets site of Belgorod rampart, typical chernozem				
Summit (4.6-m-wide) of the rampart near the wooden tower	None	13	17	0.47
Upper portion of the slope (15.5°)	Weak	11	14	0.40
Lower (concave) part of the slope (11.3°) and the footslope	Weak accumulation	None	9	0.53
Zmiev rampart (micellar-calcareous ordinary chernozem)				
Leveled summit	Weak	19	37	0.22
Upper portion of the eastern slope	Weak	15	35	0.21
Upper portion of a gentle northern slope	Moderate	None	23	0.14
Lower Trajan rampart (calcareous chernozem)				
Upper portion of the southeastern slope (3°)	Weak	8	40	0.20
Upper portion of the northeastern slope (3°)	Weak	19	30	0.15
Upper portion of the northern slope (2°–3°)	Weak	6	30	0.15
Lower portion of the northern slope	Moderate	13	26	0.13
Lower concave portion of the northern slope (3°–5°)	Weak accumulation	30	52	0.26
A ditch along the rampart	Accumulation	192	295	1.48
Uzunlar rampart (chernozem on compact clayey sediments)				
Summit	None	16	31	0.17
Upper leveled part of a slope	Weak	15	28	0.16
The rampart encircling the Mys settlement (dark chestnut soil)				
Summit	None	15	30	0.16
Upper leveled part of a slope	Weak	14	27	0.15
Upper part of the southern slope (2°)	Weak	12	26	0.14
Lower part of the southern slope (4°)	Weak accumulation	26	33	0.18
Bottom of the ditch between the rampart and the wall	Accumulation	36	84	0.46

In the catena allocated to the Nikonii settlement (1600 years), the sloping part (the length is about 22 m, and the average inclination is 6.1°) is characterized by somewhat lower reserves of the green phytomass of herbaceous vegetation with the predominance of fescue grass in comparison with the upper leveled part of this catena (according to the measurements in May, the difference is almost 2.2-fold). At the same time, the average thickness of humus horizons on the slope of this catena is just 3 cm lower than in its upper leveled part; taking into account the humus-rich B1 horizon, this difference increases to 7 cm. In the upper leveled part of the catena, the thickness of the A and A + AB1 layers reaches 39 and 66 cm, respectively (Fig. 2). Thus, within the past 16 centuries, the rates of formation of humus profiles of the soils on slopes and on leveled surfaces in the subzone of southern chernozems have been approximately similar (0.23–0.24 mm/year). The full-Holocene analogue of this catena was studied on the slope of north-northwestern aspect with a length of 32 m and inclination of 5.55°. At present, this area is used for grazing. The soils along the slope are characterized by distinct variations in the thickness of humus horizon. In the upper leveled part of the catena, the slightly solonetzic southern chernozem has a 35-cm-deep A horizon; the thickness of the full humus profile (A + AB1) reaches 55 cm. In the sloping part of the catena (length, 22 m; inclination, 4.7°), the thickness of the humus horizon decreases from 42 to 11 cm and the depth of the upper boundary of the horizon of secondary carbonate accumulations decreases from 71 to 31 cm. These changes in the morphology of soil profiles are associated with the development of erosion. The green phytomass of plants covering the eroded part of the slope is 2.7–4.9 times lower than that on the leveled surfaces. An indistinct dependence between the total thickness of humus horizons and the relief function values calculated according to equation (1) is observed. However, as well as for the soils of the catena at the settlement of Nikonii, this dependence becomes much more distinct, if we consider not the total thickness of the humus layer, but the ratio of the thickness of the transitional (AB) horizon to the thickness of the upper humus horizon A (AB : A). It is interesting to note that the soils with similar ratios of AB to A are allocated to more

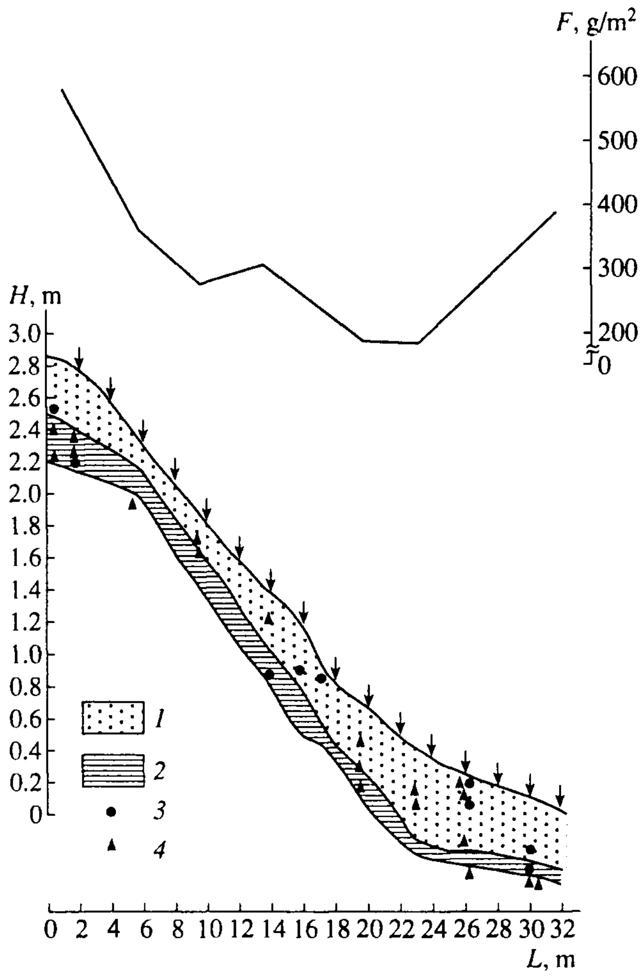

Fig. 2. The catena with southern chernozems at the Nikonii settlement (the fourth century AD). Designations: (*1*) A horizon, (*2*) AB1 horizon, (*3*) ceramic artifacts, and (*4*) limestone debris; *F*, above ground phytomass.

erodible sites in the full-Holocene catena as compared to the 1600-year-old catena.

The peculiarities of soil formation on the Zmiev rampart are conditioned by the inverse character of stratification of sediments composing the rampart. Its upper layers were constructed from carbonate-rich horizons of former soils. At present, in spite of the 16-century-old history of carbonate leaching, the topsoil horizons of the rampart are still richer in carbonates than the underlying horizons (5.6 versus 4.1% at the depth of 37–161 cm, respectively). This circumstance impedes the formation of the humus horizon in the soils of the rampart. The humus horizon (A) is underlain by a layer with distinct pedogenic structure, but without humic substances. The thickness of this layer formed by physical and biogenic processes of structuring varies from 5 to 7 cm. A similar picture is observed in the soils of the Uzunlar rampart, where the upper horizons contain up to 11.8% of $CaCO_3$.

The trenches dug across the defense lines of the Mys settlement (catena 1 crossing the outer ditch and the rampart and catena 2 crossing the inner ditch and the stone wall; Fig. 3) display evident distinctions between the soils formed on these artificial constructions within the past 1800 years. In several places, these newly formed soils were disturbed during the planting of two forest strips in the end of the 1960s. The above ground phytomass in the upper parts of slopes and on leveled surfaces reaches 260–500 g/m² (the determinations were made in June); it decreases on slopes and increases considerably in depressions (former ditches), where it may be as high as 1127 g/m² (the ditch in catena 1).

The study of soil horizons on slopes, especially, the measurement of horizon thickness, should be made with due respect to the inclination of the surface [13]; in other words, all the measurements should be done along the normal to the surface. In the catenas studied, the soils of footslopes above the ditches have a morphology similar to the morphology of background dark chestnut soils. They are composed of the upper A horizon, transitional B1 horizon, and carbonate-rich B2k horizon; the relative proportion between these horizons (with respect to their thickness) is 1 : 0.3 : 0.6. At the transition to the ditch, where the slope gradient is minimal (1°–2°), the proportion between these horizons changes in favor of the transitional B1 horizon (1 : 1.2 : 0.5).

The full-Holocene dark chestnut soil was studied 8 km to the north of the Mys settlement. The soil develops under the feather grass association and is classified as a loamy clay dark chestnut soil with residual solonetzic properties. It is composed of the following sequence of horizons: AO (0–8 cm), the sod layer of dark brown (10YR 4/4) color, with very fine granular structure; A (8–31 cm), the humus horizon of brown color (10YR 4/3), with loose granular structure, coprolites, and evident traces of eluvial processes (siliceous powdering on ped surfaces); B1 (31–50 cm), the transitional horizon of brownish gray color (10 YR 5/3) and blocky structure; B2k (50–63 cm), the carbonate-rich horizon (the effervescence is observed from 53 cm) partly impregnated by humic substances, with a bright brown color of the main mass (7.5YR 5/6) and a blocky–prismatic structure; and BCk (63–88 cm), the carbonate-illuvial horizon, yellowish brown (10YR 5/6), prismatic, very compact; soft calcareous nodules (the white eyes) appear at the depth of 82 cm; gypsum crystals are found at the depth of 2.7 m.

Knowing the absolute age of soils on artificial geomorphic surfaces, we can estimate the effect of topographic conditions of the differentiation of the soil cover along the catenas.

The structural differentiation of the soils at the footslopes of catenas 1 and 2 (the Mys settlement) is very close to the structural differentiation of full-Holocene dark chestnut soils, in which the relative proportion between the A, B1, and B2 horizons is expressed as 1 : 1 : 0.5. The

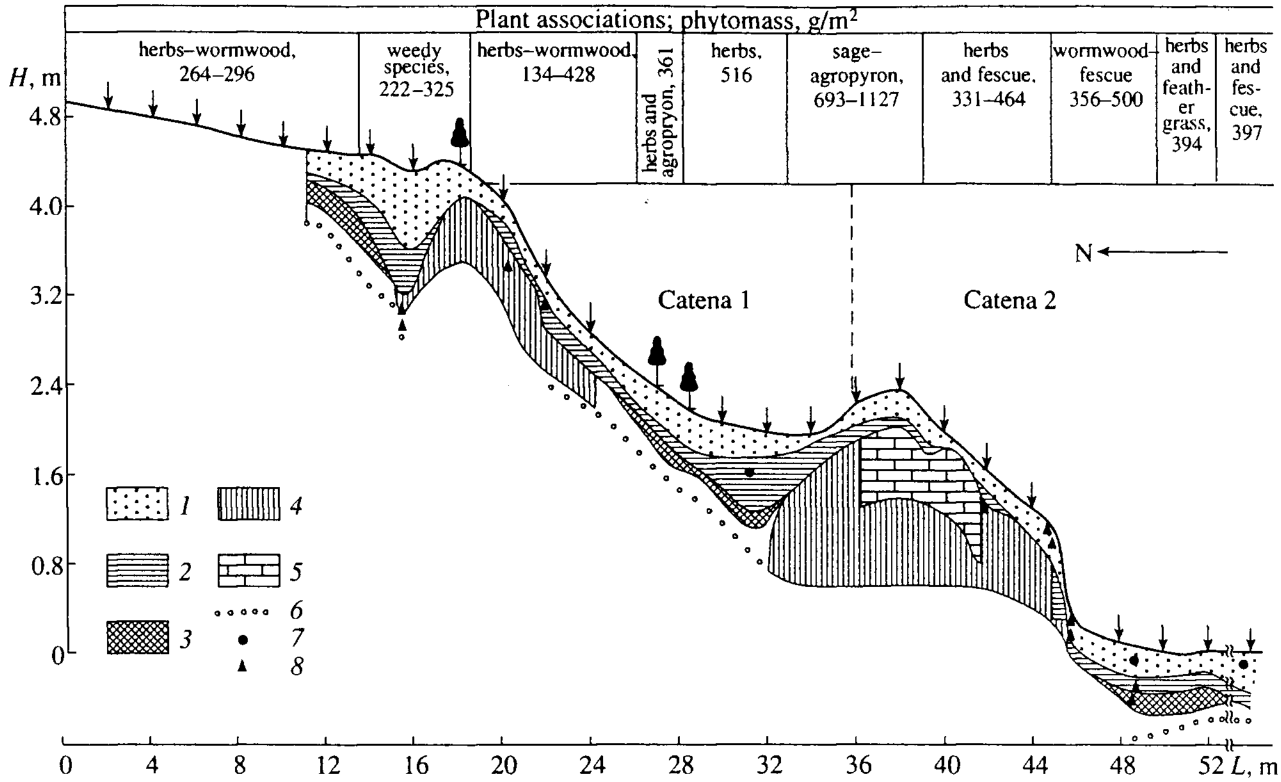

Fig. 3. The catenas with dark chestnut soils formed on defense lines of the Mys settlement (the second century AD). Designations: (*1*) A horizon, (*2*) B1 horizon, (*3*) B2 horizon, (*4*) earthy rampart, (*5*) stone (limestone) wall, (*6*) the upper boundary of the horizon with soft calcareous nodules, (*7*) ceramic artifacts and bones, and (*8*) inclusions of limestone debris.

soil profiles on the tops of the rampart and the stone wall represent unique objects that allow us to judge about the rate of zonal soil-forming processes in autonomous conditions during the Subatlantic period. According to our observations, the average rate of the development of soil humus horizons in these conditions reaches 0.16 mm/year (or 1.9 t/ha per year). It is interesting to note that the rates of humus formation on two different substrates (the loesslike loam of the rampart and limestone of the stone wall) are approximately similar. In transitional positions (on slopes), the thickness of the humus layer (A + B1) averages 28 cm, or approximately 50% of the average thickness of this layer in the surrounding full-Holocene soils (the latter was calculated from data on 144 pits). Thus, the annual increase in the thickness of the humus layer of soils on slopes is approximately equal to that on leveled surfaces (0.15 mm/year). However, taking into account the erosional processes operating on slopes, we can assume that the actual rate of humus formation in these conditions is even higher than on leveled surfaces. It is interesting to note that the thickness of the humus layer (A + B1) in background dark chestnut soils varies irregularly on slopes of different gradients [18] with a general tendency toward an increase with increasing gradients. Thus, on leveled interfluves, it averages 40.5 cm ($C_V = 14.8\%$); on slopes with inclination of 4°–9°, 45.7 cm ($C_V = 21.7\%$); and on slopes of 9°–15°, 49.5 cm ($C_V = 14.0\%$). Discussing this phenomenon, Larionov suggested that the reason for it lies in a weak differentiation of soil moistening on slopes of different gradients in conditions of the semiarid climate of dry steppes. From my point of view, the tendency toward an increase in the thickness of humus horizons on slopes, which is seen both in the full-Holocene soils and in the soils that formed on artificial geomorphic surfaces, attests to the more active processes of humus formation on slopes [19].

The humus horizon of soils in the ditches has been formed not only due to *in situ* processes, but also due to the input of humus-rich material from adjacent slopes. The rate of its formation is assessed at 0.4 mm/year. In the inner ditch (catena 1), the amount of accumulated humus-rich sediments reaches 2.7 t per meter of the ditch boundary. The ditch is surrounded by slopes of the outer rampart (from the north) and the inner stone wall (from the south), which served as the sources of the material accumulated in the ditch. The sediment transport along the ditch from the east to the west is also possible. The southern slope of the rampart has the length of 10 m and the inclination of 12° (catena 1, Fig. 3). It is known that southern slopes are more susceptible to erosion than the northern ones. At the same time, the biological turnover of substances on southern slopes is more active, which results in the more wide ratio of the active humus to the passive humus [8]. This allows us to assume that soil-forming processes (and, in particular, humus-forming processes) are more active on southern slopes than on northern ones. Taking into account the amount of material eroded from the southern slope of the rampart and accumulated in the ditch (1.3–1.5 t/ha per 1800 years), we can calculate the rate of the development of humus horizons on this slope, which equals 0.23 mm/year, or 2.4 t/ha per year. This is 1.26–1.44 times higher than the rate of soil formation in leveled autonomous positions in this area. Similar data were obtained from the analysis of the models of humus formation on slopes and in autonomous positions [19].

DISCUSSION

Starting from the works of Dokuchaev, it is believed that the morphology of soils on slopes can be adequately interpreted in terms of the activity of erosional processes differentiated by the elements of slope topography. This approach forms the basis for the diagnostics and classification of eroded soils. In turn, it is based on the assumption that the soils of slopes were similar to the soils of leveled interfluves with respect to the thickness of their humus profiles before the beginning of the agricultural development, i.e., before the beginning of active soil erosion. However, this assumption is not always true [8, 9, 38].

Already, the first works of soil scientists pointed to the fact that slope conditions (gradient, aspect, and shape) not only control the intensity of erosional processes but also create specific habitats for plants differentiated by the elements of slope topography. Thus, Kostychev [17] argued that the differences in the humus content between the soils of different elements of slopes may be conditioned not by the effect of erosion, but by the differentiation of the whole set of soil-forming factors, including the vegetation. According to his data, the chernozems in the forest-steppe zone contained up to 8.5% of humus on leveled surfaces; 8.4%, on the slopes of northern aspect; 8.2%, on the slopes of eastern and western aspects, and 5.7%, on the slopes of southern aspect. The study of chernozems in the Podol'skaya guberniya performed by Nabokikh in the beginning of the 20th century (1150 samples were analyzed) proved that the relative differences in the humus content of chernozems on slopes and on leveled surfaces did not exceed 11–12%.

Analyzing the dependence of the thickness of humus horizon on the character of surface topography (slope gradient and aspect) for different types of soils, Larionov [18] suggested that two groups of soils should be distinguished: (a) soils in which the thickness of the humus horizon is virtually independent from the relief conditions (provided that these soils have not been plowed) and (b) soils in which the thickness of humus horizons varies considerably by the elements of surface topography. The first group includes chestnut soils, sierozems, and mountainous brown forest soils. The second group includes various subtypes of chernozems. In this context, the use of the parameter of the total thickness of humus horizons in chernozems seems to be inappropriate for the analysis of the rates of erosional processes and soil-forming processes on slopes.

The study of recent soils forming on tailings in the course of their biological remediation proves that these soils have the sequence of morphological horizons resembling that in zonal soils. Soil as a holistic self-developing system can be characterized by certain proportions between its parameters. If these proportions are relatively stable, we can take them as the basis for soil diagnostics and classification. Prasolov [28] noted that in full-profile developed chernozems, the proportion between the A and the A + B horizons is close to 1.0. The ratio of the thickness of the layer A + AB to the thickness of the A horizon was suggested as a criterion for the assessment of the degree of erosion of chernozems [32]. Onishchenko [27] developed a method for the reconstruction of genetic horizons of eroded soils on the basis of the analysis of the proportions between the thickness of different genetic horizons in noneroded soils. Indeed, the horizons of natural soils (A, B1, and B2) often correlate with one another with respect to their thickness (at least, in chernozems).

The analysis of available data on the dynamics of the water regime of steppe soils and on the rates of humus formation in these soils proves that the development of steppe soils proceeds unevenly. In other words, the periods of active development of the soil profile alternate with the periods of relative stability. In this context, the analysis of proportions between the horizons (A : AB : B) may be of great interest, as these proportions might reflect the differences in conditions of soil formation during a certain stage of soil development. In general, these proportions are relatively stable for zonal soil types forming in automorphic (leveled interfluves) positions [34]. In order to reveal the effect of slope conditions on the character of soil formation, we may analyze the changes in the proportions of soil horizons at different elements of the slope. In particular, the ratio between the thickness of the transitional horizon (AB1 or B1) and the thickness of the humus horizon (A) was analyzed by us. The characteristic times of the development of these horizons are different. According to Kovda, the characteristic time of humus accumulation in the transitional horizon is 1.5 times longer than the characteristic time of humus accumulation in the upper humus horizon [16]. Thus, the AB : A ratio can be interpreted as the index of the age of a soil. The greater the age, the wider the ratio. (This conclusion follows from the assumption that the development of the humus profile in soils proceeds downwards).

In the catenas studied in the southern steppe and dry steppe subzones (Figs. 2, 3), the ratio of AB (or B) to A decreases with an increase in the value of the relief function $F(L, I)$. The alteration of this function from 60 to 130 leads to a decrease in the AB : A ratio from 1.1

to 0.1. At the same time, the total thickness of the humus profile (A + AB) does not depend on the relief function. The dependence of the AB : A ratio on slope conditions may be interpreted in the following manner. The higher potential erodibility of the soils on slopes (in comparison with the soils of leveled surfaces) induces the transformation of soil morphology so that the thickness of the transitional AB horizon decreases at the expense of an increase in the thickness of the topmost A horizon. However, the latter horizon may be subjected to active erosion. In this case, its thickness decreases and the AB : A ratio increases. Thus, this ratio may serve as an index of soil erosion. In general, the analysis of the proportions between different soil horizons on slopes may be very informative for the assessment of the rates of soil formation and soil erosion on slopes.

The notion of self-regulation of soil systems assumes more active soil formation in conditions of denudation. This is one of the important mechanisms that ensures the stabilization of the dynamic natural system "tectonic movements–soil formation–denudation and accumulation of sediments." Let us consider the mechanisms of self-regulation in detail. It can be assumed that these mechanisms have a similar nature in the soils of different ages, including eroded and deflated rejuvenated soils. During the initial stages of soil development, soil-forming processes are nonequilibrium and lead to the self-organization of the soil profile. Actually, a similar effect is observed in recently eroded soils that are also in the nonequilibrium state with the environment. In particular, the natural balance between the rates of humification and mineralization is disturbed in eroded soils. As a result, as soon as the surface is covered with plants, the coefficient of humification in eroded soils exceeds that in noneroded mature natural soils [6]. It was proven that the rate of humus accumulation on humusless rock is three to four times more active than that on humus-rich substrate [36]. It is known that the humus content in the upper layers of soil-forming rocks beneath the humus layer reaches 1.37% in strongly eroded chernozems and just 0.86–0.91% in slightly and moderately eroded chernozems [39].

Eroded soils are characterized by the nonequilibrium state and by a higher coefficient of humification in comparison with equilibrium noneroded zonal soils. However, the potential for more active humus formation in eroded soils can only be realized during the periods of attenuation of erosional processes both in annual and longer cycles (the periods of geomorphic stability) [10]. We can use two different methods to estimate the rate of humus formation in eroded soils on slopes. First, we can calculate it from data on the soil age and humus content (table) with due account for the amount of humus that has been removed from a particular soil in the course of erosion. Second, we can use a special model describing the potential rate of soil formation on slopes. The latter method seems to be very promising for the design of erosion-control measures.

Let us consider the model of the potential rate of soil formation on slopes in detail. First, we can describe the changes in the total thickness of the humus layer along the slopes using the following equation:

$$H(L) = 1/LH(l)dl, \qquad (2)$$

where $H(L)$ is the average thickness of the humus layer of soils along the line from the local divide to the given point located at a distance L from the divide and $H(l)$ is the thickness of the humus layer at an arbitrary point on the slope located at a distance l from the divide.

The thickness of the humus layer ($H(L)$, mm) for a soil catena with the soils of similar age can be calculated according to the following equation:

$$H(L) = 1/L$$
$$\times [10.85g(F_f/F_z)^{0.37}\exp(0.0044Q)(1 - ke^{-\lambda t})]dl, \qquad (3)$$

where F_f is the factual vegetation productivity, t/ha per year; F_z is the zonal (climate-controlled) productivity of vegetation, t/ha per year; Q denotes energy expenses on soil formation, MJ/m^2 per year, according to [5]; g is the correction coefficient for the effect of soil texture; t is the duration of soil formation, years; and k and λ are empiric parameters, of which the values for the main types of soils in the Russian Plain have been published in [19].

The changes in energy expenses on soil formation during the Holocene have been specially studied for automorphic (zonal) soils of steppe ecosystems [21]. The results of these studies allow us to calculate the values of $Q(t)$ and $F(t)$ for shorter periods. The redistribution of heat and water resources by the elements of slope topography can also be described. The net primary production of phytocenoses and its redistribution along the slope can be assessed from data on the biomass of the above ground parts of plants or on the mortmass stored in the soil.

If we consider a catena composed of full-Holocene soils, equation (3) can be simplified via grouping of constant values:

$$H(L) = A/L(g(l)F_f^{0.37}(l)\exp(0.0044Q(l))dl, \qquad (4)$$

where A is an empirical coefficient equal to 3.7 for the chernozems of the forest-steppe zone, 3.8 for ordinary chernozems, 4.4 for southern chernozems and dark chestnut soils, and 6.0 for chestnut soils. Calculations by equation (4) can be made via application of well-known methods of numerical integration (the method of trapeze or the Simpson method). In order to obtain the values of H averaged for a certain area, we have to use double integration taking into account the variations in distribution of soil-forming factors across and along the slope.

The equation for calculation of the thickness of the humus layer (and, hence, the rate of soil formation) on the slopes under croplands has the same shape, but it has to be supplemented with experimental or calculated data on the rate of annual soil erosion.

Equation (4) allows us to calculate the potential thickness of the humus layer of soils located at different positions along a slope. This calculation can be made both for the full-Holocene soils and for the soils of a certain age. Knowing the potential thickness of the humus layer, we can compare it with factual data and, thus, estimate the effect of erosional processes. The study of catenary conjugations of soils with known zero-moment of soil formation, including the study of soil catenas in the areas of archeological excavations, may be very promising for this purpose. In this respect, the collaboration of soil scientists and archeologists might be very beneficial for both sciences.

CONCLUSIONS

(1) The soils formed on dated surfaces (360–1800 years) in the forest-steppe and steppe zones of the Russian Plain are characterized by a relatively uniform thickness of the humus horizon both on leveled surfaces and in the erosion-susceptible parts of slopes. This phenomenon can be explained by a higher rate of soil formation on slopes as compared to leveled interfluves.

(2) In soil catenas under natural vegetation, the thickness of the humus layer virtually does not depend on the value of the relief function, which takes into account the shape, aspect, gradient, and length of a slope; at the same time, the increase in the relief function value is accompanied by the general thinning of the humus layer and a rapid increase in the ratio of the thickness of the transitional AB (or B1) horizon to the thickness of the A horizon.

(3) The ratio of AB (B1) to A horizons reflects the degree of soil development. With an increase in the age of soils and corresponding decrease in the rate of humus horizon development, the AB : A ratio increases.

(4) Special catenary studies of soils in combination with modeling the potential rate of soil development in different parts of slopes seem to be very promising for the assessment of the rates of soil erosion and soil formation on slopes.

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