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Soil Reproduction in Steppe Ecosystems of Different Ages

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Abstract—Features of the development of steppe chernozems were established based on the study of soils of different age groups at archaeological sites. Differences in the formation of phytomass and morphological maturity of the soil profile in the recovery of different age successions were shown. A regional model of the humus horizon steppe soil over time allowed us to estimate the time interval at which the processes of humus accumulation and morphological maturity of the soil profile are relatively at equilibrium, viz., 1700–1900 years.

Keywords: steppe ecosystem, the reproduction of soils, human disturbance, archaeological monuments, Late Holocene

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INTRODUCTION

Ecological restoration of steppe biomes, first of all, implies the management of revegetation. Due to the different durations of the reproduction processes of plant and soil cover, steppe vegetation plays a pivotal role, although it is clear that the results of ecological restoration measures are strongly dependent on the soil system. Since the soil is a bioskeletal system, natural fertility as a result of the development of natural soil formation processes, including biogeochemical transformation of a mineral soil, should be considered as a resource that is difficult to create. By analogy with biological and landscape diversity, it has been suggested [1] that one should emphasize “soil diversity,” viz., exhaustible non-renewable resources. In the steppe zone, such unique soils as those with different times on the barrows, settlements, and fortification earth structures, along with their fully Holocene counterparts that usually occur in specially protected natural areas, should be included in the Red Book of soils.

The experience from such developments already exists [2–3]. The floristic variety on just one mound is impressive: for 44 mounds in the study (with ages from 700 to 5000 years), out of 900 Ukrainian steppe species of flora we found 209 species of plants in various microzonation habitats [4]. In addition, when sorted by the time axis in the form of chronosequence the land cover changes that recover after heterochronic anthropogenic disturbances provide informative space–time process models of ecological renaturation.

According to the recommendations of EUROSITE, Toolkit Management Planning [5] in the areas of environmental planning should be conducted as active management to maintain habitats and biodiversity and full control of the reproduction of biotopes. An effective solution of this problem can contribute to a deeper understanding of interdependent (syngenetic) bonds in the soil–plant system. Identification of environmental and soil relationships at the quantitative level, taking the regional and local features of scenic areas into account, is among the most important and urgent problems of soil ecology [6], which is one of the independent sciences of the biospheric class.

MATERIALS AND METHODS

A field study of landscapes that formed during the late Holocene was conducted in the Republic of Crimea (Ukraine) and Krasnodar region (Russia). The organization of soil-evolutionary studies on the Kerch and Taman peninsulas is favored by the abundance of ancient monuments of different times with formed soils in a peculiar but quite homogeneous bioclimatic situation. In the reality of the ancient times, the European and Asian parts of the Bosporan state correspond to two subregions that are distinctive in their geological, soil, geographic and bioclimatic features. The Kerch hilly ridge steppe as a physical geographic area differs from the area to the west (the Steppe Crimea) and the Taman Peninsula is not like other parts of the Kuban that are located to the east.

On the Kerch peninsula the average annual precipitation ranges from 330–350 to 400 mm. The climate is very dry, moderately hot (the average annual temperature is 11°C, the average temperature in July is 22.6–23.3°C) with a mild winter. According to the mean annual values, the coefficient of humidity (of Ivanov–Vysotskii) varies from 0.50 in the northwest and 0.38 in the south. Typically in the Kerch monticulate area, a feather grass-sagebrush steppe in the southern and calcareous chernozems and chestnut and alkaline soils are combined with petrophytic shrub–forb–grass steppes on undeveloped gravel soils of the chernozem type and chestnut soils. On the Kerch Peninsula the beginning of the formation of a soil cover out of chernozems of a modern type occurred 5200 years ago [7] (according to calibrated dates, 6000 years ago).

With the variety of original landscapes on the territory of the Kerch Peninsula the following ecological situation is the closest to studied objects. It is associated with low-lying geocomplexes with dark brown and southern chernozem soils under the xero-, petro- and halophytic varieties of bunchgrass steppes with the significant participation of semi shrubs of wormwood and osier stands [8]. Many unplowed areas can contribute to the rapid restoration of disturbed lands. One of the biggest sites (6000–7000 hectares) of feather grass steppes, Chigini, which is preserved near the village in the Zolotoe Leninskii district in Crimea contains formations of *Stipeta braunerii*, *S. grafiana*, *S. capillatae*, and *S. borysthenicae* [9].

On the Taman Peninsula, whose conditional border goes from Anapa to the west coast of Kurchanskii liman, the climate is softened because of the coastal position (less contrast occurs). Heat-supply conditions are characterized by a high sum of positive temperatures (up to 3600–3800°C). Average annual temperatures range between 10–14°C, on average 11°C. Summer is hot (the average temperature in July is 21–24°C). The average temperature in the winter period is minus 0.3°C (in the coldest month (January) – 2 to –4°C).

The Taman climate is not very humid (the annual precipitation is 350–430 mm of rainfall and averages about 400 mm) and has a mild winter. The precipitation maximum falls in two seasons: winter and autumn [10].The typical prolixity of the humus soil profiles can be explained by the significant participation of descending currents of moisture during periods of low evaporation (72% of the annual precipitation falls in the winter, spring, and autumn).

On the Taman Peninsula the power consumption for soil formation (according to V.R. Volobuev) is 954 (843–1013) MJ/(year · m^2). These values are higher than in the Kerch peninsula, due to higher moisture and a better degree of heat supply. In the soil cover of the Taman Peninsula, southern chernozems dominate. These are predominantly slightly argillaceous mycelial-calcareous powerful and medium thick chernozems on loess loams, partly on sandy clay alluvial deposits and antequaternary salt clays. The brown chernozems of Taman (chernozems of the South European facies) contain 3–3.5% humus in their upper layer [10].

As an example let us take a description of the morphological structure of fully Holocene soil (southern chernozem heavy loam) under the Crimean vermouth and sheep fescue association (0.8 km west of the village of Taman): A (0–28 cm), from 16 cm browning is noted, AB$_1$ (28–74 cm), from 66 cm the first signs of illuviation occur, B$_{1Ca}$ (74–93 cm) below the BC horizon.

Recently, in soil and evolutionary studies a method for studying uneven soils has been evaluated. These soils are grouped according to scales of the internal time of the studied process in chronorows (a set of analyzed soils that formed on the same substrate under similar bioclimatic conditions but that differ in their relative ages).The next stage, which contributes to the understanding of the laws of the development of soils, is connected with the transition to soil chronofunctions. To perform this task, the change of soil properties is coordinated with the ages that are established by quantified dating methods (e.g., archaeological methods).

Studies of the morphological structure of soil profiles on archaeological sites were performed in soil profiles, thus revealing a set of new soil horizons after the end of the existence of residential areas or the last filling for embankments. Analytical works were performed according to standard procedures: humus by the Turin method, gross nitrogen (N) by the Kjeldahl method, soil acidity (pH) was determined potentiometrically, and carbonates by the acidimetric method.

Dated succession was characterized through the type of phytocenosis and total projective cover (TPC). To a certain extent, this diagnoses the arrival of plant material that enters the soil and participates in the formation of humus, as well as the degree of protection of soil from water erosion and deflation.

To obtain the dependence of the humus horizon of soils on their age it is appropriate to form a soil chronorow on anthropogenic structures in the maximum possible time range. Therefore, the objects of this study were the territories of ancient cities, villages, and settlements, burial mounds, ancient earth mounds and earth mounds of World War II in so-called belligerent (from Latin *belligero*: to wage war) landscapes [11], and mining dumps. The studied soils of different ages are characterized by a chronointerval of soil formation from 15 to 3500 years. For comparison, we used data on the morphology of zonal (fully Holocene) soils. The research objects are listed according to the geographical principle and are marked in Fig. 1.

1. Crimean Republic. Romanov bay. Semenovka, a settlement. Chernozem on heavy clay. Different grass association.

2. Peninsula Kazantip, Quarantine (Zhelyaevsky) cape. Mysovka (Mysovoye II). Settlement 2nd c. B.C. Chernozem on ash pan. Sparse grass vegetation.

3. Kazantip peninsula, the coast of the Tatar bay. Hillfort Heraclius 3rd c. A.D. calcareous chernozem on eluvium of limestone. Zhitnyakovaya association.

4. 29 km west of Kerch. Uzunlarskii or Akkosov (on the maps, Tatar), landscape height 2.6 m, width (with moat) 34 m, the end of the 1st millennium B.C. (different authors from 9th to the 4th c. B.C.), strength-

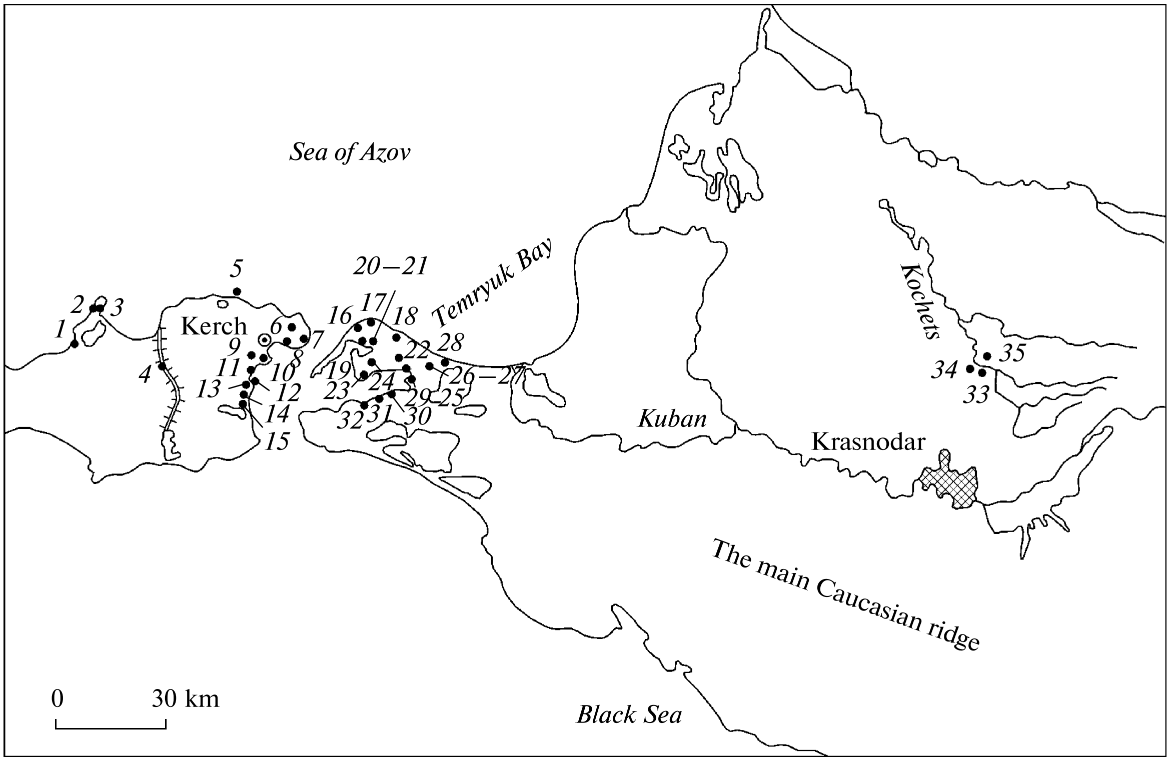

Fig. 1. Objects of soil and chronological research within the Kerch and Taman region and adjacent territories. Explanations in the text.

ened by the Bosporan king Asandr (47 to 16 B.C.). Chernozem on heavy clay. Feather grass and fescue association with the participation of mastitis.

5. Cape Zyuk. Zenon Chersonese (hillfort), 7th c. A.D. Medium loam. Ruderal motley grasses.

6. Kamenka, settlement. Humified mound. Motley Association (fescue, sagebrush Crimean, milkweed, and yarrow).

7. Yenikale, fortress. Rampart of the upper castle. Medium loam. Fescue motley association (TPC = 60%).

8. Mirmeky, city. Light loam carbonate. Campfire association.

9. Neighborhood of Kerch, a mound to the north from the second Serpent Mound. Heterogeneous earth embankment. Heavy loam. Grass–forb association.

10/1. Panticapaeum, an ancient city. Bottom terrace. Gravelly loam. The soil under the embankment of archaeological excavations.

10/2. Kerch, fortress 19th c., earthen embankment. Clay with gravel. Wheatgrass–motley group (TPC = 80%).

11. Tyritake, city. Diverse cultural layer. Ruderal vegetation (wheat grass, cutter, and mosses).

12. Kerch, Arshintsevo district, dam. Mound of tobacco clay. Fescue association (TPC = 55–60%).

13. Nymphaeum, city. Medium loam. Forb–grass association (TPC = 85–90%).

14. Geroevka II, settlement. Cultural layer. Medium loam. Forb–grass association (fescue, bluegrass, sagebrush, alfalfa sickle, and plantain lantsentny).

15. Geroevka I, settlement. Medium loam. Different herbal–fescue association (TPC = 60–70%).

16. Northwestern edge of the village of Ilyich. The area between the rampart and cliff of the indigenous coast of the Kerch Strait. Hillfort (Trebizond) (4th to 6th c. B.C.). Average loess loam. The soil is blocked by archaeological discharge.

17. Northeast village of Ilyich. Batareika. A fortress emerged at the turn of the era and was finally defeated in 576 by the turkuts. According to other data, life in the fortress ended in the 9th c. A.D. In the humus horizon the newly-formed soil and at the boundary of the AB and B soil horizons we came across ceramics that were dated as 2nd to 5th centuries A.D. at a depth of 29 cm, viz., an amphora handle 2nd–3rd centuries A.D. Loam is medium sandy. Grass–fescue association (fescue, kochia, and Austrian wormwood).

18. The southern coast of Temryuk bay. Hillfort Kuchugura II (4th to 3rd centuries B.C. to 3rd to 4th centuries A.D.).

Calcareous sandy loam. Dumetum, cereals. Ibid. Loam average carbonate. Cereal grasses.

19. North Coast of Dinsky Gulf, mound Batareika I (1st through 4th c. A.D., according to new data [12] existed in the 6th c. A.D.). Sandy loam. Crimea wormwood–fescue association (TPC = 40%).

20/1. Batareika village. Hillfort Batareika II (end of 2nd century A.D. to 4th c. A.D., existed in the 6th c. A.D. [12]. Loam medium carbonate. Cereal grasses, small pasture digression (TPC = 95%).

20/2. Ibid. Archaeological excavation in the ancient city, founded by the expedition of N.I. Sokolsky in 1962–1965. Calcareous loess loam. Weeds modified by pasture digression.

21. North coast of Dinsky bay, 0.25 km to SW of Batareika village. Parapet of a machine-gun point in 1943. Heavy loam carbonate. Forb–grass vegetation (wheat grass, Austrian sagebrush).

22. Settlement of Krasnoarmeiskoe (1st c. B.C. to 5th c. A.D.). Medium loam. Forb–grass vegetation.

23. 1.2 km to the southwest of Fontalovskaya village. The top of the mound height is 4 m. Newly formed soil of the Late Scythian Epoch. Loam average carbonate. Weeds.

24. North Coast of Taman Bay western region village Garkusha, Patra city (5th c. B.C. to the 70s of the 4th c. A.D.). Medium loam. The soil is covered with archaeological discharge.

25/1. Easter of Jubileinyi village. Cimmerian rampart, total length is 1.2 km, the width at the base is up to 30 m and the height is about 5 m. Loam average carbonate. Grass vegetation with soil lichens.

25/2. A German bunker also occurs on the side of the rampart. Medium loam. Cereal grasses.

26. Suburb of the village Za Rodinu. Preserved archaeological site, Tamanskii Tolos i Rezidenziya Khrisaliska after excavations in 1975. Medium loam. The vegetation is dominated by bluegrass (TPC = 50%).

27. Two km to the southwest of the village of Za rodinu, Veselyi mound, height, 12 m. Surface material dates from Scythian. Medium loam. Austrian wormwood–fescue association (TPC = 30%).

28. Coast of Temryuk Bay, barrier of Ahtanizovskii liman, a defensive rampart of Fort Tiramba (built in the 1st c. B.C., destroyed in the 1st c. A.D., but life at the fort continued until the 3rd c. A.D.).Medium loam, transitional to light. Grasses and herbs.

29. East coast of Taman Bay, the ancient city of Kepy (the first half of 6th c. B.C. to 4th c. A.D., Huns destroyed it shortly before 545 [12]). Light loam. Sparse vegetation (osier stand, summer cypress, solonechnic piliferous, and early ripe horehound) and pasture.

30. One km to the west from the Sennaya station. The ancient city of Phanagoria (6th c. B.C. to the 7th c. A.D.). Medium loam. Cereal grasses (fescue and wheatgrass with osier stand and thrift).

31/1. The southern coast of the Taman Bay, at the eastern edge of Taman village. Fanagoriyskaya fortress. Lower rampart 1795. Heavy loam. Xerophytic steppe vegetation.

31/2. In the eastern part of the fortress near the bastion of St. Peter. A bunker 1943. Medium loam. Cereal grasses.

32/1. The northwestern edge of Taman. Coastal zone. Hillfort Hermonassa. Soil on the layer with ceramics 5th to 4th century B.C. Light loam. Fescue association (projective cover 60%), pasture digression.

32/2. Northern edge of Taman. Newly formed soil layer with artifacts of the 1st century A.D. and a layer up to the 12th century (Tmutarakan hillfort). Medium loam. Krymskopolynnaya association (TPC = 20%).

In addition, to better provide the model with empirical data we involved studies on the territories adjacent to Taman.

33/1. Krasnodar region, Dinsky district, left bank of the Kochets river, Novyi, first floodplain terrace, mound height approx. 9 m. Herb–wheatgrass vegetation (bedstraw and sage).

33/2. A 10 m high mound with triangulation point. Wheatgrass–hawk association (TPC = 80%).

34. At 1.2 km to the west of 33/1, mound height approx. 9 m. Herb–wheatgrass vegetation (bedstraw and sage).

35. At 8 km to NE of 33/1, a mound with a broad apex, triangulation point, a height of 7 m. Grass vegetation, shrubs on the slopes.

The data we obtained under field conditions and as a result of analytical determinations are integrated into a soil-chronological database (DB), which contains more than 400 descriptions of soil-genetic profiles of newly formed soils on uneven surfaces of different landscape and geographical regions of Eastern Europe [13]. The database object description is structured in four sections: (1) spatial characteristics (location, location, photo, and plant associations), (2) description of the soil profile and conditions of soil formation, the age of the soil, and (3) soil-genetic description on horizons, (4) and the morphological physico-chemical properties of soils. Information from the database is used to simulate the process of regeneration of steppe soils over time.

RESULTS AND DISCUSSION

Generalization of the results of the study of soils of different ages at archeological monuments in the Kerch–Taman region was performed via a model of the dependence of the thickness of the humus horizon (H) of newly formed soils on their age. As stated previously in a study of soils of different ages [14] significant differences H in soils that were formed in the areas of distribution and the black soil of the southern chernozems and dark-chestnut soils in the last 2600 years are not seen in Crimea. To determine the possibility of combining soil-historical data of the Kerch and Taman arrays we performed modeling that

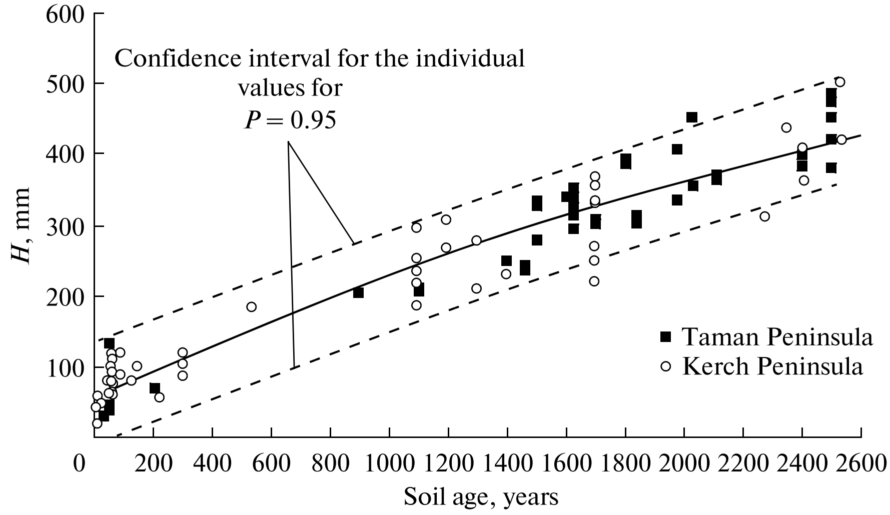

Fig. 2. The dependence of the thickness of the humus horizon of the southern steppe chernozems on time (according to research in the territory of the Kerch and Taman peninsulas).

depended on the H of southern chernozems of their age separately for each array. Comparison of the calculated data that were obtained by the two models showed no significant difference (Kolmogorov—Smirnov test, $P = 0.95$) between the models. As a result, an integrated array of empirical data for the soils of the steppe zone of the Kerch—Taman region was made for the calculation of the model parameters. A plot of the humus horizons of southern chernozems and their ages is shown in Fig. 2.

Adaptive transformation of the structure of restored steppe communities occurred in a syngenetic manner with the formation of humus horizon of new soil surfaces, which were recreated by anthropogenic relief formation. In the archaeological landscape the landscape dependence indicates the total amount of phytomass of steppe ecological systems by the age of the succession. The above-ground phytomass autogenous successions that were deformed by cultural layers from 1600—3500 in age that are dominated by feather grass is 7.1 t/ha and the fescue associations contribute 4.8 t/ha.

Based on the average long-term data [15], for the fescue—feather grass association the above- and below-ground mass (in the 0—20 cm layer) provide 12 t/ha of vegetable matter annually, which is equivalent to a speed of humus formation of 2.4—2.5 t /ha. Based on the speed of the expansion of the individual structural parts of the mortmass and their contents of critical organogenic elements (Ca, K, and P) it was calculated that via litter on the soil surface and the remains from roots (0—20 cm) feather grass provides 58 and 131 kg/ha of mineral elements and fescue (*Festuca valesiaca*) provides 38 and 66 kg/ha, respectively. Thus, the soil under feather grass receives 1.8 times more organogenic elements than under fescue and the value of feather grass to the process of humus is higher.

The formation of a series of communities with a supply of litter (steppe felt) is important to the process of soil formation. In the investigated steppe ecosystems with ages from 16 to 35 centuries average stocks of litter were 198 ± 39 g/m^2. Feather grass communities with a two-layer litter structure (upper horizon mortmass (slightly decomposed) and lower (highly decomposed)) in contact with the soil horizon are decomposed more rapidly and nitrogen and ash elements (K, Ca, Mg, and S) invade [16].

During the estimation of phytomass reserves in uneven recovery successions there were fewer differences in virgin fescue associations than in feather grass (1.1—1.2 vs. 1.3—1.9 times). Apparently, this may indicate a greater environmental correspondence between fescue that has reached maturity and the level of soil fertility. It is all the more remarkable given that, after 55 years of the “Old” preserve site in Askania Nova in the succession of dry steppe vegetation the main trend can clearly be seen, viz., the transformation of feather grass cenoses into fescue [17].

It is natural that vegetation reflects environmental factors more quickly than soil. If plant communities form a phytomass within 80—84% of the level of the indigenous communities in fully Holocene soil in 2000—3000 years, humus soil horizon for ages of 16—18 centuries is 39—42% of the standard and for 22—35 centuries it is 47—62%.

Thus, even under favorable climatic conditions climax status in the plant community is defined by the component of the ecosystem with the most characteristic time, viz., the edaphotope. Comparisons with the indigenous community found that differences in structures persist even after 16—35 centuries of self-development. Differences of productivity that are due to the developmental maturity of the soil do not prevent the preservation and a duration of the succession of several thousand years [18]. If definite chronological boundaries can be established for the quasi-climax state of plant communities, then the equilibrium state of the edaphotope is heterochronous; the soil, in particular, the maximum processes of leaching (decarbonation), humus accumulation, and the accumulation of silt differ by orders of magnitude [19].

Evolution must be understood as a continuous gradual ordering, i.e., the complexity of soil or soil cover in the process of self development [20]. Ontogenetic development of the soil is a nonlinear process, which is characterized by a complex sequence of dynamic equilibrium transitions to an equilibrium state. The general nature of the ontogenetic development of the soil as an organic inert system can be described as a growth model, which has already been tested for biological and ecological systems.

We introduce the following notation: H is the thickness of humus soil horizon, mm; $H_{\lim}$ is the limiting limiting value H in these bioclimatic conditions for a specific particle-size distribution of parent rocks, mm; t is the time of soil formation, years; and λ is a constant that depends on the bioclimatic conditions of soil formation.

Given that the overall form of the changes in the resource characteristics of the soil (the humus horizon (H) and the content (total) of humus (Γ) in it) during the Holocene depends first of all on the zonal–provincial limits of soil parameters ($H_{\lim}$, $\Gamma_{\lim}$) and is a function of time ($F(t)$), each of these processes, in particular, the formation of humus horizon, can be written as

$$dH/dt = H_t' = \lambda H_{\lim} F(t). \qquad (1)$$

To justify the form of the function of time, an analogy can be made to the directed morphogenetic processes in automorphic soils during the Holocene [21] with the general pattern of growth processes in the ecosystem. Graphically, both processes appear to be S-shaped (sigmoidal) curves. Among the methods of approximating their functions, viz., the logistical and Gompertz methods [22], the latter is preferred because of its asymmetry, which results in great stretching of the upper branch (the attenuation of growth is slow). Therefore, the process of formation of a humus layer can be written as

$$H_t = H_{\lim}(\exp(-e^{a+\lambda t})), \qquad (2)$$

where a is a constant. Then, the first derivative is as follows:

$$H_t' = -\lambda H_{\lim} e^{a+\lambda t} \exp(-e^{a+\lambda t}). \qquad (3)$$

After integration of (3) and transition to the timeline of the Holocene, the dependence for the formation of the humus horizon in time takes the form

$$H_t = H_{\lim}(\exp(-\exp(a+\lambda t)) - \exp(-\exp(a - 2000\lambda))), \qquad (4)$$

where t ranges from -2000 to 0 (the prehistory of soils) and from 0 to 10000 years (the Holocene). Note that at the stage of prehistory in theory the creation of primary source rock fertility is probabilistic in nature because the paleogeographic reconstructions are based on indirect evidence.

With respect to applied problems, the analytical form of the curve is the most adequate but can be somewhat simplified by equation (4). To this end, we write the differential equation with multiple variables as:

$$dH/dt = \lambda(H_{\lim} - H(t)), \qquad (5)$$

where $H_{\lim} - H(t)$ is the zonal value of the potential of the formation of the humus horizon, whose rate is determined by λ.

After integration we obtain an equation of the form

$$\ln|H(t) - H_{\lim}| = -\lambda t + \ln C. \qquad (6)$$

Assuming that at $t = 0$ and $H(t) = 0$, we determine the value of the constant C:

$$C = H_{\lim}\exp(t_0\lambda). \qquad (7)$$

After substituting (7) into (6) we obtain the equation

$$H_t = H_{\lim}(1 - \exp(t_0\lambda)\exp(-\lambda t)), \qquad (8)$$

which after substituting exp ($t_0\lambda$) for k takes the form of an ordinary exponential function

$$H_t = H_{\lim}(1 - k\exp(-\lambda t)), \qquad (9)$$

where k can be interpreted as the level of the primary fertile soil rocks (for a fully Holocene soil) or the initial amount of organic matter in the cultural layers and bulk substrates of human origin and λ are the process-rate dynamics, which have the dimension of the inverse of time (1/year).

It was noted in [23] that the exponential growth modes are determined not only by development, which is under constant internal and external conditions, but whether conditions change in certain ranges that do not exceed some critical value.

According to the regional soil-chronological studies via equation (9) we have a "calibration" model of the development of the humus horizon of the chernozems of the southern steppe subzone (H_t) over time (t) with the calculation of the regional settings.

The dependence is shown graphically in Fig. 2 and is most adequately reflected in an analytical formula of the form

$$H_t = 800(1 - 0.931e^{-0.00026t}), \qquad (10)$$

where H_t is the humus horizon, mm; t is the age of the soil, years; and e is the base of the natural logarithm ($e = 2.718$).

Upon analysis of chronorows the phasic development of soil and the heterochronology of the leading processes of soil formation transformations become apparent [24]. The achievement of the relative "maturity" of the production–destruction processes of an ecosystem exerts a significant influence on the

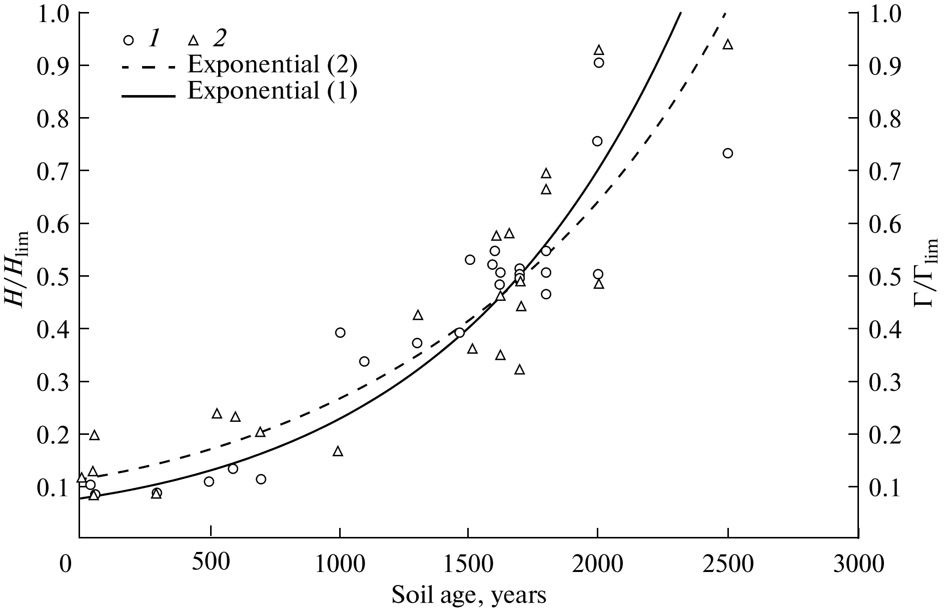

Fig. 3. Changing the humus horizon thickness and humus reserves in soils of Kerch and Taman region: *1*, the actual values of the thickness of the humus horizon, normalized by its limiting value ($H/H_{\lim}$); *2*, the actual values of humus reserves, normalized by its limiting value ($\Gamma/\Gamma_{\lim}$).

sequence of steps of pedogenesis, which is closely related to the intensity of the flow rate of elementary soil processes of the metamorphism of organic matter. The period of the rapid growth of the productivity of the phytocenosis ($n \cdot 10$, $n \cdot 100$ years) is followed by (with consideration of the inertia of the soil) the predominance of the processes of the accumulation of humic substances over their fixation in the depth profile. The stabilization of the productive capabilities of plant communities at the quasi-climax level results in a transition to the stage of the development of the "slow growth" of the soil with the relative prevalence of eluvial processes ($n \cdot 1000$ years). One feature of this phase is the close to complete formation profile of paragenetic aggregate horizons and other diagnostic features of a zonal soil that characterize the period of the "maturity" of the soil [25].

For the initial phase of soil development (the first decade) the values of the velocities of formation are almost two orders of magnitude greater than for soil of a millennial age. This indicates the high capacity of natural geosystems to restore the desired mode of operation of a key component, viz., soil.

The features of the changes of other soil properties are associated with the patterns of the formation of the thickness of the soil humus horizon of newly formed soils. The most informative include: the supply of organic matter in the humus horizon, the leaching of carbonates (the position of the "boiling" line from 10% HCl) and (or) their distribution in the soil profile, the degree of "maturity" of the organic matter (the ratio of humic and fulvic acids, the contents of carbon and nitrogen), the extent of the soil structure, the redistribution of clay particles in the profile, etc.

Comparison of the morphological maturity of the newly formed soil humus horizons points to a regular feature of their progressive development during 2500 years of soil formation. The average rate of formation of the humus horizon in the steppe chernozems over this period was 0.16 mm/year, which is comparable with the figures for the more favorable bioclimatic conditions of the forest steppe zone [26]. This is due to the high mobility of the newly formed organic matter in the profile of steppe soils under intensive soaking during periods of low evaporation. In general, the development of the humus profile of the soils is characterized by fairly rapid achievement of a quasi-equilibrium state (the thickness and contents of the humus). In newly formed soils enrichment with nitrogen is usually at a middle or high level (less than 8).

Significantly, the cultural layers of archaeological sites in the southern steppe climate already begin to leach in the first 10 years from the beginning of soil formation. In a period of 1000–1500 years a limiting of the level of the leaching of carbonates in the humus soil profile can be achieved. The investigated soils have an alkaline soil solution reaction; thus, the age-related differences of this indicator are weakly expressed. This is explained by the specific geochemical landscape, which experiences a constant influence of alkali ions from marine aerosols due to the high alkalinity of the original parent rocks.

Comparison of the patterns of formation of the humus horizon of the steppe soils and the humus reserves in it (Fig. 3) allowed us to estimate the time interval in which the processes of humus accumulation and morphological maturity of the soil profile were in relative equilibrium, viz., 1700–1900.

CONCLUSIONS

The development of morphogenetic processes in soils and, above all, the formation of the humus layer of a soil, has an inherently deterministic trend; an analogy can be seen in the patterns of flow processes in ecosystems. The biogeochemical cycle plays a determining role in the reproduction of soil, including the processes of complexes with organic residues, their transformation, mineralization, and humification. Under bioclimatic conditions in the steppe zone (with a coefficient of humidification of 0.4–0.5) after 2–3 millenia of ecological renaturation in anthropogenically transformed geosystems the above-ground phytomass in an autogenous succession reaches values that in relative terms are 80–84% of the mean annual efficiency of indigenous productive ecosystems. By this time, the average annual rate of depositing energy reserves of organic matter in the soil humus horizons reaches 3.1 MJ/m^2.

The formation of a sufficient mass and a diverse biochemical composition of plant material determines the dynamic parameters of the process of humus accumulation; this defined the progressive rate of the formation of the humus horizon of steppe soils during the period up to 1700–1800. This age of the soil corresponds to the thickness of the soil humus profile of steppe chernozems, with the most intense roots at 32–33 cm, which is 52–54% of the maximum power. Then (in 1800–1900), apparently the morphostructural organization of the soil profile was enhanced by more active soil-formation processes: leaching, migration of the products of humification, etc. As the succession ages perennial species that form local channels in the soil profile play an increasing role (the movement of roots, cracks, surface macroaggregates, etc.); as a result the migration of organic substances occurs (but not in a frontal manner).

The changing land cover presented in the time range of $n \cdot 10$–$n \cdot 1000$ years can be regarded as a spatio–temporal model of the process of renaturation of steppe ecosystems in a regime close to the natural reproduction of their biological and biostructural components.

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