Agrogenic Transformation of Soils in the Dry Steppe Zone under the Impact of Antique and Recent Land Management Practices

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Abstract—Virgin, cultivated, and old-arable soils have been studied in the area of Olbia, one of the antique poleis in the northern part of the Black Sea region. It is shown that the soils cultivated during the antique time still preserve some features differing them from their virgin analogues. In the course of agrogenic evolution, progressive changes in the morphology of dry steppe soils are not accompanied by the improvement of soil aggregation at lower levels. Macromorphological indices attest to the enhanced development of humification processes and leaching of carbonates and soluble salts in the soils cultivated during the antique time. At the same time, a number of soil degradation processes are vividly manifested in the cultivated soils. It is suggested that this process can be referred to as the soil allopseudomorphosis.

INTRODUCTION

Changes in the properties and fertility of soils under the impact of cultivation are rather ambiguous and depend on the balance between yield production and human-controlled pedogenesis. A paradox of agricultural soils is that the soil fertility may both increase and decrease upon a sharp rise in the intensity of biogeochemical cycles in the agrocenoses [21].

Numerous data on changes in soil properties under the impact of intensive farming technologies (including soil tillage practices, application of fertilizers, etc.) have been accumulated in the recent decades. Most of them have been obtained in recently developed areas, the duration of agricultural exploitation of which is often less than a century. It is interesting to study soil processes with long characteristic times that take place in the long-cultivated soils, including the soils that were used by ancient civilizations. In particular, the record of long-term agricultural impacts in the soil profile is of great interest for archaeologists [34].

As shown in [35], valuable information on changes in the soil properties under the impact of long-term agricultural practices can be obtained from the study of soils of ancient agricultural terraces. Such terraces may date back to about 2500 years in the New World, 2000–4000 years in western Europe and the Mediterranean region, and up to 5000 years in the Middle East. An example of sustainable use of soils for a period of more than 1500 years can be found on terraces in the Andes [36, 37].

In this paper, the results of soil studies in the area of Olbia—an antique Greek polis with centuries-long history in the Black Sea region—are discussed.

OBJECTS AND METHODS

The study area is found between the Berezan–Sosik liman of the lagoon type and the Bug liman in the estuary part of the Yuzhnyi Bug River (the term liman designates a long and sinuous bay that forms upon submergence of river estuaries or coastal gullies under the sea). This territory belongs to Nikolaev oblast of Ukraine (Fig. 1) and is occupied by the dry steppe zone. From the south, it is bordered by waters of the Dnieper–Bug liman and the Black Sea. The northern boundary of study area corresponds to the boundary between southern solonetzic chernozems and dark chestnut soils. Large-scale soil surveys of the area performed in 1962–1963 showed that medium and heavy loamy dark chestnut soils predominate in the Lower Bug basin. According to the new classification system of Ukrainian soils, these soils are referred to as low-humus heavy and medium loamy dark chestnut soils [26]. In the new Russian soil classification system [14], they are distinguished within the order of low-humus carbonate-accumulative soils as the subtype of typical chestnut soils. The cultivated soils of the region belong to the subtype of calcareous typical agrochernozems.

The mean annual precipitation in the Lower Bug area is about 330 mm; according to the long-term (since 1877) records of the Ochakov weather station, annual precipitation may vary by about 2.5 times (from 218 mm in 1911 to 526 mm in 1938) [1]. Within the interfluve between the Berezan–Sosik and Bug limans, the mean annual precipitation reaches 340 mm [1]. The maximum annual precipitation was registered at the Tiligulo-Berezanka weather station in 1952 and reached 629 mm. Precipitation during the cold season does not exceed 34% of the annual precipitation. The maximum depth of soil freezing is 47 cm. The northern

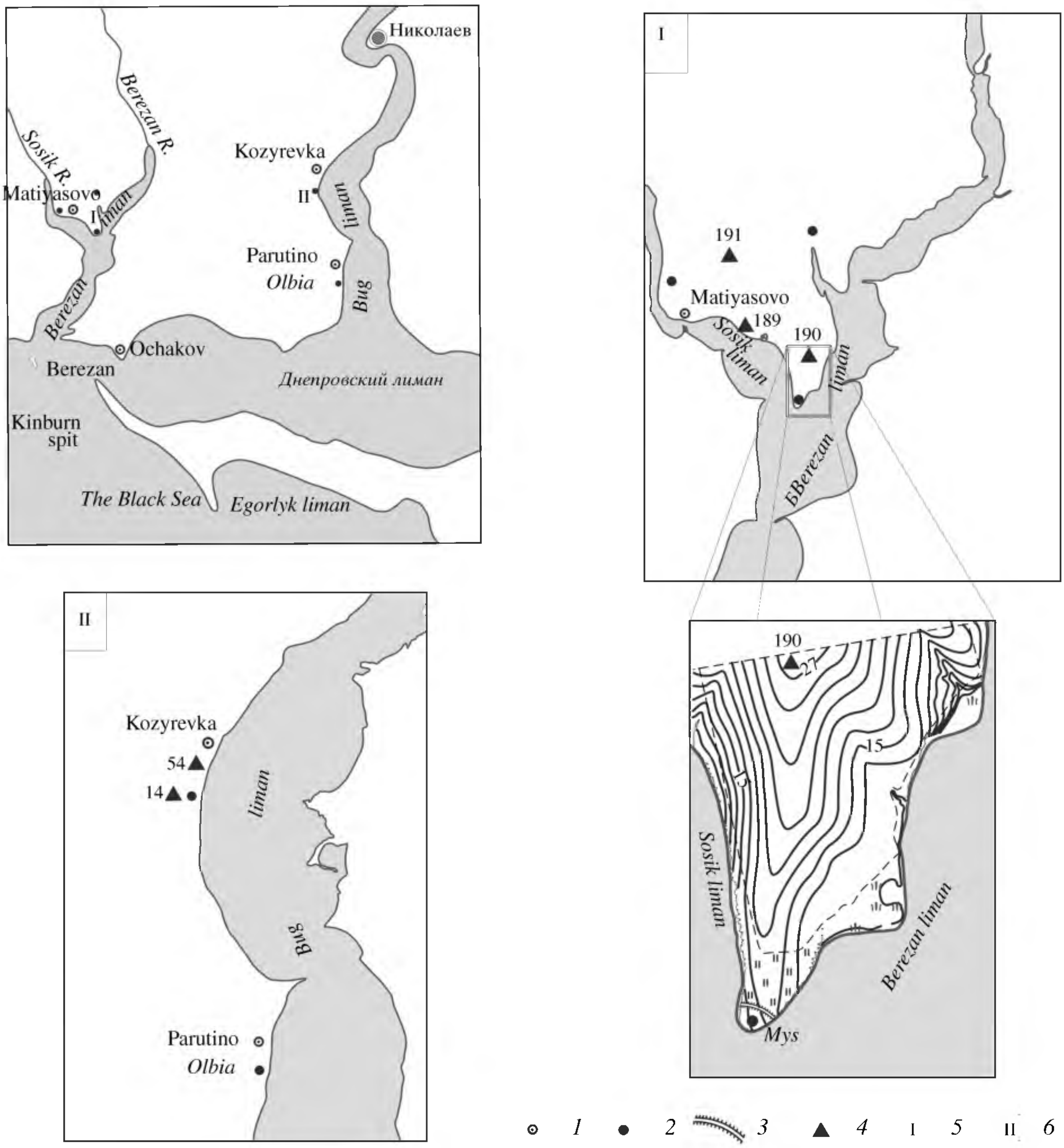

Fig. 1. Location of soil objects studied in rural area of ancient Olbia: (*1*) modern settlements, (*2*) antique settlements, (*3*) rampart and ditch around the antique fortress, (*4*) soil pits; (*5*) key site I (between the Berezan and Sosik limans), and (*6*) key site II (in the lower reaches of the Bug River).

boundary of the studied area is found 14 km to the north of the Black Sea coast. It corresponds to a sharp decrease in the velocity of winds; winds that may induce soil erosion are frequent in the coastal region (100%) and less frequent in the inland part (30%) [17]. In general, the study area belongs to the dry steppe zone with low values of the hydrothermic coefficient (0.59 in the Lower Bug reaches and 0.60 in the Berezan district).

Geologically, it represents an aggradational plain of the Late Pliocene–Quaternary age; the plain is subjected to a descending neotectonic movement. The thickness of the loess cover within the plain reaches 30–40 m; the horizon with a considerable concentration of soluble salts is found at a depth of 2–5 m.

In the period of colonization by ancient Greeks, the dry steppe zone on the northern coast of the Black Sea was in center of the antique Olbia polis that existed there from the beginning of the sixth century BC to the end of the 4th century AD. The analysis of special works [3, 29] showed that active agricultural exploitation of the area around Olbia could last for about 680–690 years. During this period, more than 140 settlements of local farmers were established, including both small farmsteads and relatively large settlements (up to 50–70 ha) [3].

Soil sequences arranged with respect to the character and duration of agrogenic impacts were studied under similar conditions of the relief and surface hydrology. The following soil objects were chosen: (1) a virgin soil and an abandoned (under long-term fallow) soil cultivated during the antique time and (2) a virgin soil, a long-cultivated soil (a soil cultivated in the time of ancient Olbia and in the recent century), and a recently (<100 years) developed soil.

Large-scale aerial photos and topographic, soil, and land use maps compiled in different periods were used to locate the particular pits to be studied. The position of studied soils in the evolutionary sequence was verified with the use of all available data, including data on the soil structure and humus distribution in the profile. During the second year, soil trenches were dug in the areas of key soil pits in order to study spatial variability in the particular characteristics of the soil profiles with due account for variations in the micro- and nanotopography, plant associations, and other local soil-forming factors.

A comparison of virgin medium loamy dark chestnut soils (pits 13 and 54) with the soil cultivated in the antique time and then abandoned (pit 14) was performed for two plateau-like plots 0.4 and 1.8 km to the south of the settlement of Kozyrka (Fig. 1). These plots had approximately similar hypsometric position (47 m a.s.l.) and were covered by the herbaceous–fescue vegetation under conditions of moderate grazing loads. During the study of pit 13, special attention was paid to the variability in the morphological indices of soil horizons. Two additional trenches (2.5 and 2.7 m in length) were studied, in which the depths of soil horizons were thoroughly measured in 44 points. Pit 54 was additionally described in one of these trenches 8 m to the south of pit 13. On the second plot with the soil cultivated in the antique time and then abandoned (pit 14), the depths of soil horizons were measured in 28 points.

These data were used to calculate the mean depths of soil horizons in the virgin (pit 54) and abandoned (pit 14) soils and to estimate the error of the mean with the use of Stundent's criterion at the 5% significance level.

At the beginning of the Christian era, the settlement of Mys was founded 30 km to the west of ancient Olbia on the cape between the Sosik and Berezan limans [5]. These limans were formed in estuary parts of two small rivers: the Sosik (or Sasyk) River and the Berezan River. The discoverer of this ancient settlement Goshkevich believed that he found the antique town of Odess [8]. In the 1940s–1960s, archaeologists considered this place to be the place of the Scopella settlement known from the antique sources. The settlement was encircled by a system of fortified ramparts and trenches; these objects were used in the pedoarchaeological investigations [19]. In the context of our study, the unique geographic position of this settlement is important, as it easy to determine the area that could be used for agricultural purposes.

Three objects were studied in this area: a virgin soil, a soil presumably cultivated in the antique time, and a soil cultivated during the past century. The corresponding plots were numbered as follows.

Plot 1 (pit 189) was found 1.7 km to the southeast of the village of Matiayasovo, on a plateau-like slightly inclined (0.75°) surface (8 m a.s.l.) of the bank of the Sosik liman. The surface topography was complicated by microdepressions. Herbs and grasses (wheat grass, June grass, wormwood, Statice, etc.) with mosses between dense sod patches grew on the field subjected to moderate grazing pressure. The soil was classified as a slightly solonetzic heavy loamy dark chestnut soil. According to cartographic materials and characteristic soil features, this plot has never been plowed.

Plot 2 (pit 190) was found in the area that could be plowed in the antique time. At present, it represents an agrolandscape on the elevated (27 m a.s.l.) and slightly inclined (0.5°) automorphic surface.

Plot 3 (pit 191) was found beyond the zone of possible agricultural development in the antique time (its area was estimated at 450 ha), 4.8 km to the north of the Mys settlement on the automorphic surface at the same level as plot 2. The slope of the surface was 0.6°.

The soils on these plots were studied in 3-m-long trenches. The depths of soil horizons were measured on the walls of the trenches through every 10 cm. For the upper humus horizons on the cultivated plots (plots 2 and 3), the field data on their thickness were corrected taking into account the difference between their bulk densities and the equilibrium bulk density of the humus horizon in the virgin soil (1.27 g/cm^3). The soil color characteristics were determined with the use of Munsell color charts.

The results obtained during the field study were processed by the factorial ANOVA aimed to estimate the difference between the three soils on the basis of data on the thickness of their humus horizons and the entire humus profile (A + B) and on the depths of the upper and lower boundaries of the horizon with the maximum concentration of carbonates. The factorial ANOVA made it possible to estimate the effect of studied factors on the difference between the groups. The results of our calculations showed that the difference between the morphological parameters of studied soil profiles as related to the history of their agrogenic evolution is statistically reliable for all the genetic horizons, except for the A horizon.

To estimate errors in measurements of the thickness of soil horizons, a hypothesis of normal distribution of the data (at $n \geq 30$) was accepted [23]. Thus, we obtained estimates of the errors with probability P = 0.95 according to the following equation:

$$\Delta_{0.95} = \frac{t_H \sigma_{Xi}}{\sqrt{N}},$$

where t_H is the normalized quantile of normal distribution at the given probability.

As the soils were studied in Ukraine, soil horizons were designated using the traditional Russian system and the system of soil horizons developed by A.N. Sokolovskii in 1930 and accepted by Ukrainian soil scientists.

The physiochemical soil properties were determined by routine methods; the organic carbon content was determined by the wet combustion method (according to Tyurin); the quantitative composition of soil humus, by the method of Kononova–Bel'chikova; the adsorbed Ca and Mg, via the soil treatment with 1 N NaCl solution and titration with Trilon B; and the adsorbed Na and K, via the soil treatment with NH_4Cl followed by the determination of displaced Na and K on a flame photometer. The Chang–Jackson method (in modification by Askinazi, Ginzburg, and Lebedeva) was applied to study mineral phosphates. The magnetic susceptibility and mineralogical composition of the fractions > 1 μm were determined according to Chang (1974, Russian translation); the mineralogical composition of the clay (<1 μm) fraction was determined on a DRON-3 X-ray diffractometer in the Institute of Physicochemical and Biological Problems of Soil Science of the Russian Academy of Science in Pushchino.

HISTORY OF AGRICULTURAL DEVELOPMENT

The dark chestnut soil studied in pit 14 could be used as a cropland in the antique time. Archaeologists discovered the settlement of Kozyrka XII (or Chuprinova Balka) near the studied pit. According to their data, this settlement existed in 525–475 and 430–325 BC [3, pp. 29, 58]. Thus, this plot could be used for agriculture in the ancient time at least for 150 years. The effect of agricultural treatments in that time could be enhanced by humidization of the climate in the middle of the first millennium BC. No evidences of the further use of this territory for crop growing since the antique time (i.e., during the past 2300 years) have been found.

The antique Olbia polis existed for more than 1000 years. Thus, land plots around it and smaller settlements (between the Berezan and Bug limans) could be used for agriculture (with some interruptions in time) for about 700 years. In contrast to this part of the studied territory, the Mys settlement on the cape between the Berezan and Sosik limans was founded later, during the Roman time, as a fortress to protect the northeastern borders of the empire from Sarmatian tribes. This settlement was also a local trading and agrarian center [5]. At the late stage, it existed in the hostile barbarian environment of the tribes dwelling to the north of the Black Sea. The Roman settlement was destroyed by Goths in the middle of the third century AD. According to the archaeological data [29, p. 190], cereals (wheat, barley, and millet) were the main crops grown in the antique Olbia. The soil was tilled with double-moldboard plows. The soil studied in pit 190 could be tilled for about 250 years (as the Mys settlement was not destroyed by Sarmatians in the middle of the second century AD [5, p. 134], the agricultural development of this territory could have a continuous character). After the destruction of the Roman fortress, this territory was abandoned. The land remained in an idle state for 1650 years. The new stage of its agricultural development began about a century ago.

In the context of our study, it was important to delineate the area that could be plowed in the antique time. In 1913, V.I. Goshkevich (the discoverer of the ancient Mys settlement) compiled a map [8], according to which the potential area of the settlement was estimated at 2.1 ha. The ditch around the settlement was dug in the second century AD [13]. After this, a gully was formed in this ditch. It is probable that some part of the ancient settlement was destroyed by the gully erosion. Also, the retreat of the shoreline with a rate of 13 mm/year should be taken into account. It can be supposed that the ancient Mys settlement occupied about 3 ha. Archaeologists determined the dependence of the size of ancient settlements in the area of Olbia on their population [29]. In the extensive agricultural systems, the area of cultivated land should be about 7.3–10.6 ha per capita [32]. On the basis of these data, the area of the land that could be used as a cropland around the antique settlement of Mys was estimated at 270 ha (provided that the settlement area was 2 ha) or 450 ha (provided that the settlement area was 3 ha). As this settlement was mainly a fortress [5, p. 85], the first estimate seems to be more realistic. Then, the boundary of the potentially cultivated area (270 ha) was determined with due account for the suitability of local landscapes for cropland. As the settlement was found in the southern part of the cape between the two limans, the cultivated land could only be found to the north of the settlement, within a boundary at a distance of 2.4 km.

Pit 190 was studied in this area. It characterizes the soil that could be cultivated in the antique time (during the Roman period). The situation is complicated by the fact that one more ancient settlement (the Mys-2 settlement) founded by Greeks existed 2 km to the north of the Mys settlement in the seventh–fifth centuries BC. The area around it could also be cultivated. However, according to archaeologists, this was not a permanent settlement. It is probable that it was used for temporary housing of fishermen and herdsmen [3].

Plot 3 (pit 191) was studied beyond the zone of the maximum potential area of cultivation (450 ha) in the antique time.

The modern stage of agricultural development in the area began after settling of Russians in Ochakov oblast annexed in 1791 (according to a treaty with Turkey). The village of Matiyasovo (Agaf'evka) was founded 5 km to the north of the antique Mys settlement in approximately 1789–1794. The map of land use in the Kherson gubernia suggests that just about 5% of the local land was plowed in the 1820s. The active agricultural development of this territory began in the 1830s. Cereal crops were mainly grown. In 1882, the portion of plowed area reached the average value typical of the entire gubernia (52.8%) [20]. At the end of the 19th century, a new local farmstead was founded to the east of the village of Matiaysovo. Later, it was known as the village of Solontsy that existed until 1982. At the beginning of the 20th century, the portion of cropland reached 70% [30]. Thus, the duration of the recent period of agricultural development of this territory is estimated at about 90–110 years. If we take into account the antique epoch, the total duration of the agricultural impact on the local soils may be extended to 350 years.

At present, plots 2 and 3 belong to the local farm of Zhemchuzhnyi. They are used in the intensive crop rotation system (fallow, 4 years under cereals and legumes, and 4 years under tilled crops).

RESULTS AND DISCUSSION

Differences in the morphology of the virgin soil and the soil cultivated in the antique time and then abandoned can be judged from the descriptions of pits 54 and 14, respectively. The soil profile studied in pit 54 has the following morphology (indices of soil horizons are given according to the "Classification and Diagnostics of Soils of the Soviet Union" (1977) and according to Sokolovskii (1930)).

A0 (Hed), 0–6(8) cm. The sod horizon; dark gray, with fine granular structure.

A (He), 7–33 cm. The humus horizon; dark brown, with siliceous powdering; granular and crumb peds of 2–7 mm in size compose about 37% of the soil mass; the portion of coprolites in the aggregates (the degree of biogeneity of the soil structure) is estimated at 22%.

B1 (Hpi), 33–49 cm. Brown; the degree of biogeneity and the structural arrangement are similar to those in the A horizon, except for the lower content of silt-size (<0.25 mm) microaggregates (9% versus 13–15% in the A horizon).

B2 (Phi/k), 49–57 cm. Heterogeneous in color, with grayish humus mottles; fine crumb structure; the line of effervescence from HCl is found at a depth of 50–54 cm; the lowermost part of the horizon contains carbonate concentrations.

Bca (Pk/h), 57–68 cm. Pale-colored, with weakly developed structure.

BC (Pk(h)), 68–85 cm. Loess with separate humus tongues.

This soil can be classified as a slightly solonetzic dark chestnut soil with some features of eluviation (siliceous powdering in the A horizon) and illuviation. The classical profile of dark chestnut soils was described in less continental conditions of the Askania Nova Reserve [4, p. 101]. The soil studied by us differs from that classical profile in a thicker (by 10 cm) humus horizon, a somewhat greater (by 6 cm) depth of the entire humus profile and a higher (by 10 cm) occurrence of carbonate concentrations (calcareous nodules) in the soil profile, though the line of effervescence is found at the same depth.

The soil cultivated in the antique time and then abandoned (pit 14) has the following characteristic features.

A0 (Hed), 0–6 cm. The sod horizon; relatively loose.

A (He), 6–41 cm. Gray, with whitish siliceous powdering on ped faces; the bulk density is the same as in the virgin soil (1.2 g/cm^3); aggregates of 2–7 mm in size compose 46% of the soil mass; silt-size microaggregates compose 9%; the biogeneity of the soil structure (the portion of coprolites) is 18%. In the layer of 20–40 cm, inclusions of pottery fragments and slag are found.

The material of this layer displays effervescence from 10% HCl. The micromorphological analysis of thin sections was performed by S.V. Gubin from the Institute of Physicochemical and Biological Problems of Soil Science (Pushchino). It demonstrated the presence of small shells of mollusks in the aggregates; some microaggregates of the second and third orders also contained dispersed forms of calcite. The latter could be formed in this soil after it was abandoned 2300 years ago.

B1 (Hpi), 41–53 cm. Dark pale, more compact; with fine crumb structure; the biogeneity of the structure decreases.

B2 (Ph/k), 53–60 cm. Dark pale with reddish tint in the lower part; evenly colored by humic substances; siliceous powdering is seen on ped faces.

Bca (Pk/h), 60–68 cm. Dark pale, with siliceous powdering on ped faces.

BC (Pk), 68–95 cm. The horizon with maximum concentration of calcareous nodules (white eyes); contains a krotovina at a depth of 85–91 cm.

Artifacts attesting to the anthropogenic impact on this soil in the past were found in the A horizon (pottery fragments at a depth of 18–34 cm, slag (12–52 cm), and bones (34–40 cm)) and deeper (pottery fragments in the layer of 56–58 cm and slag in the layer of 57–64 cm).

In the antique time, the agroclimatic conditions were favorable for the development of agriculture. According to paleogeographic data [13], the local climate in the fifth–third centuries BC was relatively close to the modern climate. However, the annual amount of

Table 1. Mean depths (M, cm) of soil horizons in the virgin and formerly cultivated dark chestnut soils

Horizons	$M \pm t_{05}S_x$	I	Variance (S^2)	Coefficient of variation, %
Virgin plot, pit 54				
A(He)	32.7 ± 0.6	28–36	3.3	5.6
Bl(Hpi)	16.3 ± 0.8	12–21	6.4	15.6
B2(Phi)	8.9 ± 0.6	5–15	5.5	26.4
Bca(Pk(h))	10.3 ± 1.1	5–21	16.6	39.5
Profile thickness	68.1 ± 0.8	60–79	–	–
Depth of effervescence	51.8 ± 1.8	48–56	6.8	5.0
Depth of calcareous nodules	56.5 ± 1.2	54–60	3.1	3.1
Abandoned land (since the 4th century BC), pit 14				
A(He)	41.2 ± 1.2	35–47	9.6	7.5
Bl(Hpi)	11.6 ± 1.8	7–17	4.7	18.7
B2(Ph/k)	7.4 ± 3.9	3–14	10.2	42.9
Bca(Pk/h)	7.3 ± 10.9	4–15	4.9	30.3
Profile thickness	67.5 ± 1.0	64–74	–	–
Depth of calcareous nodules	78.5 ± 1.0	76–81	–	–

Note: M is the mean; S_x is standard deviation, t is Student's criterion at the 95% probability level, and I is the interval (cm).

precipitation at the beginning of that period was greater than that at present.

Statistical data on the morphology of the virgin soil (pit 54) and the soil plowed in the antique time (pit 14) are summarized in Table 1. The values of the variation coefficient calculated for separate soil horizons show that the variability in their thicknesses increases down the soil profiles. The maximum variability in the formerly plowed soil was found for the B2 horizon that contained dark brown humus tongues and mottles; in the virgin soil, the maximum variability was found for the Bca horizon with humus mottles and streaks, including the streaks along large biogenic pores.

The least significant differences were calculated for thicknesses of soil horizons measured in the virgin soil and in the soil plowed in the antique time. According to our data, the thickness of the B2 horizon is the same in both soils. In the formerly plowed soil, the thickness of the B1 horizon is 4.7 cm greater than that in the virgin soil (P = 0.90), and the thickness of the A horizon is 8.5 cm greater (at P = 0.999).

The structural state of soils depends on many processes: humus accumulation, leaching of carbonates, transformation of soil minerals, etc. All these processes have their own cyclic dynamics. Thus, clay minerals are subjected to swell–shrink processes under the impact of seasonal cycles of soil moistening and drying and freezing–thawing. Changes in the biogenic porosity depend on seasonal changes of phytocenoses on plowed fields and on the impact of tillage operations, etc. The soil structuring factor (K_s) can be used for quantitative estimates of changes in the soil structure. Its values in the virgin soils (for the A horizon) reach 1.8 (pit 54) and 1.5 (Askania Nova). In the soil cultivated in the antique time, the K_s value is 2.8; in the soil cultivated during the past century, 0.5; in the soil cultivated for a longer period, 0.4 (Table 2). In the virgin and abandoned soils, granular and coarse granular aggregates predominate; moreover, the portion of these aggregates in the soil cultivated during the antique time and then abandoned is 7% higher than that in the virgin soil.

The results of mineralogical analyses (Table 3) indicate that the soils subjected to agrogenesis are enriched in kaolinite and impoverished in illite, which can be due to the active migration of Ca in the alkaline medium of the tilled soils. The cultivated soils are also marked by a somewhat heavier texture (Table 2) and lower magnetic susceptibility.

The humus horizon of the formerly cultivated soil contains some features inherited from the previous stage of the agrogenic soil development. The brown tint in the color of this horizon is less distinct; the content of the clay is 5.2% lower than that in the virgin soil, which may be due to the additional aggregation of clay in the stable microaggregates. The stability of aggregate-size fractions of 2–3 and 5–7 mm in diameter is greater in the formerly cultivated soil. This soil is also richer in carbonates. The humus content in the formerly cultivated soil is lower than that in the virgin soil. At the same time, the portions of the first (most mobile) fraction of humic acids and the aggressive fraction of fulvic acids (fraction 1-a) in the composition of soil humus (Table 5) are greater. The indices of the structural state

Table 2. Structural organization of the virgin and formerly cultivated dark chestnut soils (the content of particular aggregate fractions (%) is given above the line, and the content of coprolites in the fractions (% of the mass) is given under the line)

Aggregate shape	Aggregate size, mm	Askania Nova, the Staryi plot, A horizon (9–28 cm)	Nikolaev oblast, Ochakov district; plots to the south of the village of Kozyrka		
			pit 54, 0–20 cm	pit 54, 20–40 cm	pit 14, 0–20 cm
Coarse crumb	22–28 (26)*	None	2.2 / None	14.1 / None	None
Columnar	14–22 (17–28)*	″	3.4 / None	2.1 / None	″
Crumb	10–20	7.6 / None	9.6 / None	9.0 / None	9.3 / None
Fine crumb	7–10	3.4 / None	6.5 / 44	9.6 / 25	7.9 / Нет
	5–7	4.1 / 39	8.3 / 55	10.1 / 46	7.1 / 21
Angular blocky		0.5 / None	None		
Fine angular blocky	5–7	0.5 / None	″		
Coarse granular	3–5	14.7 / 61	17.8 / 55	18.6 / 51	23.4 / 46
Granular	2–3	15.6 / 51	10.8 / 47	8.9 / 37	15.6 / 36
	1–2	24.6 / 39	15.3 / Not det.	9.4 / Not det.	16.9 / Not det.
Fine granular	0.5–1	11 / Not det.	6.4 / Not det.	4.2 / Not det.	5.8 / Not det.
Silty	0.25–0.5	9.4 / Not det.	5.9 / Not det.	4.6 / Not det.	5.2 / Not det.
	<0.25	7.8 / Not det.	13.8 / Not det.	9.4 / Not det.	8.8 / Not det.

* Values for pit 54 are given in parentheses.

Table 3. Mineralogical composition (%) of the clay (<1 μm) and coarser fractions in the studied soil sequence

Study object	Pit no.	Depth, cm	Primary minerals (> 1 μm)			Secondary minerals (<1 μm)		
			quartz	plagioclases	potash feldspars	hydromica	smectite	kaolinite and chlorite
Virgin plot	13	0–20	65	9	10	80	7	13
Abandoned soil	14	0–20*	62	7	14	78	9	14

* Abundant inclusions of pottery fragments are present in this horizon.

Table 4. Particle-size (above the line) and microaggregate-size (under the line) distribution and specific magnetic susceptibility (χ, $n \times 10^{-6}$ SI units) in the layer of 0–20 cm of the virgin and formerly plowed soils

Study object	Pit no.	Solid phase density, g/cm^3	Particle size, mm; particle content, %						$\chi(>1\ \mu m)$ / $\chi(<1\ \mu m)$
			1–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
Virgin plot	13	2.62	3/32	17/30	40/30	9/3	5/2	26/3	49/74
Abandoned soil	14	2.72	2/22	15/25	41/41	12/5	10/3	20/4	44/63

of the formerly cultivated soil are generally worse than those in the virgin soil. This concerns the values of the water stability of soil aggregates, the soil microaggregation factor calculated according to Vadyunina [7], and the coefficient of structural dispersal calculated according to Kachinskii. The mean weighted diameter of water-stable soil aggregates reaches 2.4 mm in the virgin soil and decreases to 1.1 mm in the formerly plowed soil. Under the impact of the 150-year-long cultivation in the antique time, the morphology of the entire profile was changed. The humus profile in this soil was 4 cm thicker than that in the virgin soil. The frontal downward migration of humus masked the previously formed humus tongues in the B2 horizon, the solonetzic features became less distinct, the portion of Mg cations in the adsorption complex became lower, the upper boundary of the carbonate-illuvial horizon lowered by 22 cm, and the siliceous powdering on the peds became more pronounced in the deep horizons.

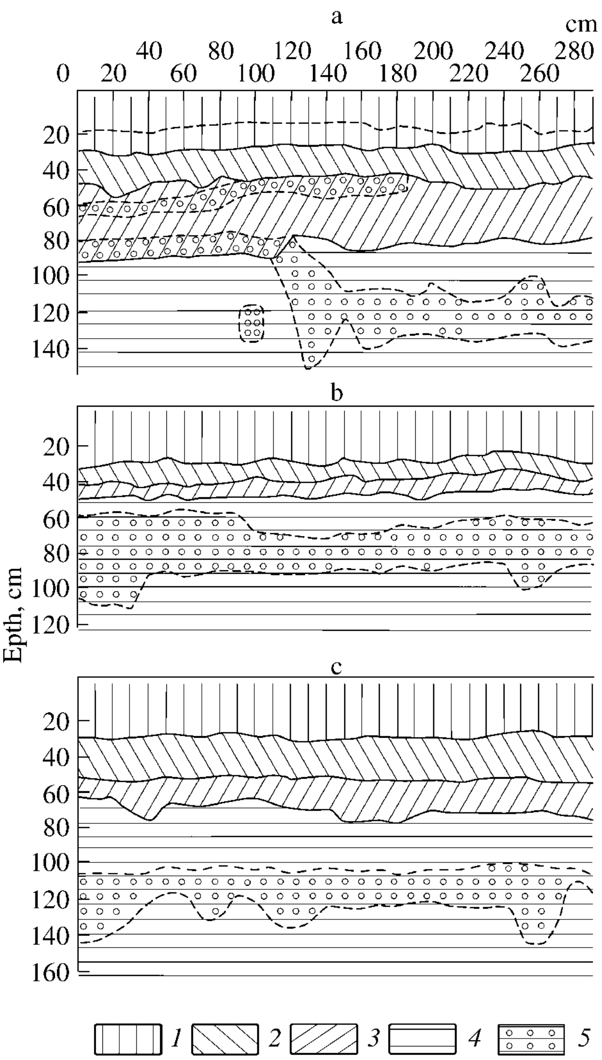

Fig. 2. Schematic drawings of the morphology of studied soils: (a) pit 189, (b) pit 191, and (c) pit 190. Genetic horizons: (*1*) A, (*2*) B1, (*3*) B2, (*4*) BC, and (*5*) Bca (with the presence of calcareous nodules).

Various direct and indirect impacts of agrogenesis on the soil formation can be clearly seen from the comparison of the studied trenches (Fig. 2). This figure also displays the degree of spatial variability in the morphometric parameters of the virgin and formerly cultivated soils.

The soils studied in the area of the Mys settlement (plots 1–3) are described below. The soil of plot 1 (virgin soil, pit 189) has the following morphology.

Ad (Hed), 0–8 cm. The sod horizon; dark yellowish brown (10YR 4/4), with fine granular structure.

A (He), 8–31 cm. The humus horizon; dark brown (10YR 4/3), with fine granular structure; abundant coprolites. From the depth of 22 cm, the color becomes somewhat brighter; siliceous powdering is seen on ped faces.

B1 (Hpi), 31–50 cm. The transitional horizon; dark brown (10YR 5/3), with angular blocky structure.

B2 (Phi/k), 50–61 cm. The lower part of the transitional horizon; unevenly colored by humus; reddish brown (7.5YR 5/6); blocky–prismatic structure; effervescent from the depth of 50–58 cm; carbonate concentrations are present in the form of pseudomycelium and calcareous nodules.

BCca (Pik(h)), 61–88 cm. The carbonate-illuvial horizon; yellowish brown (10YR 5/6), with prismatic structure; the second maximum of calcite nodules is present in the layer of 81–92 cm; in the microdepressions, the layer with calcite nodules becomes thicker

Table 5. Major properties of the virgin and formerly cultivated (abandoned 2300 years ago) medium loamy dark chestnut soils

Soil properties	Pit 013		Pit 014	
Depth, cm	0–20	20–40	0–20	20–40
Humus, %	4.21	2.99	3.25	2.73
C_{ha}/C_{fa}	1.21	2.56	3.45	1.80
Humification degree, %	28.3	37.0	36.7	22.8
C_{ha} bound with Ca	82.6	84.7	77.3	70.6
C_{ha} bound with R_2O_3 and free	17.4	15.3	22.8	29.4
Humin, %	48.4	48.6	52.7	64.6
C_{org} extracted by mineral acids	6.5	9.8	7.9	9.5
N_{total}, %	0.271	0.176	0.288	0.182
C/N	9.0	9.8	6.5	8.7
$CaCO_3$	None	None	1.68	2.69
pH_{H_2O}	7.3	Not. det.	7.7	Not. det.
pH_{KCl}	6.95	"	7.4	"
Adsorbed bases, meq/100 g				
Ca	21.6	23.8	21.6	20.4
Mg	6.4	0.2	2.4	3.6
Na	0.43	0.43	0.53	0.62
Coefficient of aggregation	2.50	1.65	2.51	2.22
Structuring factor (by Vadyunina)	61	Not. det.	57	Not. det.
Dispersal factor (by Kachinskii)	10	"	19	"
Crumb-like aggregates, %	61.9	59.0	60.3	55.6
Water-stable aggregates >0.25 mm, %	83.2	62.6	65.2	57.9
Mean weighted diameter of water-stable aggregates, mm	2.36	0.87	1.08	0.67
Coefficient of aggregate water stability	0.94	0.86	0.86	0.82
Coefficient of aggregation	0.38	0.27	0.30	0.29
Content of nonaggregated particles	17.9	24.1	20.4	24.8
Porosity, %	54.6	Not. det.	56.6	Not. det.
Particle-size distribution, %:				
physical sand (> 0.01 mm)	60.45	"	58.43	"
physical clay (<0.01 mm)	39.52	"	41.57	"
clay (<0.001 mm)	25.37	"	20.15	"
Microaggregate-size distribution,%:				
$\Sigma > 0.01$ mm	92.93	"	87.89	"
$\Sigma < 0.01$ mm	7.07	"	12.11	"
$\Sigma < 0.001$ mm	2.49	"	3.76	"
Mineral phosphate, mg/100 g:				
total	37.42	"	97.98	"
loosely bound	0.52	"	1.88	"
A1–P	1.20	"	18.80	"
Fe–P	2.30	"	1.70	"
Ca–P	33.40	"	75.60	"

Table 6. Statistical characteristics of the thickness of soil horizons (n = 30)

Indices	Statistical characteristics of the thickness of soil horizons $\frac{M \pm \Delta 0.95}{V}$		
	virgin soil, pit 189	century-old cropland, pit 191	cropland in the 1st–3rd centuries AD and in the past century, pit 190
A(H)	$\frac{31 \pm 1}{6}$	$\frac{29 \pm 1}{6}$	$\frac{31 \pm 1}{5}$
B1(Hp)	$\frac{18 \pm 1}{12}$	$\frac{10 \pm 1}{18}$	$\frac{24 \pm 1}{7}$
B2(Ph)	$\frac{38 \pm 2}{12}$	$\frac{8 \pm 1}{17}$	$\frac{18 \pm 1}{22}$
Bca(Pk/ih)	$\frac{22 \pm 4}{55}$	$\frac{30 \pm 4}{33}$	$\frac{25 \pm 3}{39}$
BC(Pk)	22	$\frac{30 \pm 3}{26}$	$\frac{18 \pm 3}{53}$
Total thickness of the profile (A + B1 + B2 + Bca), cm	109	77	98
Depth of effervescence, cm	58	38	73
Upper boundary of the horizon with calcareous nodules	$\frac{96 \pm 6}{16}$	$\frac{64 \pm 2}{8}$	$\frac{106 \pm 1}{2}$
Humus content in the A horizon, %	4.4	2.5	2.3

Note: M is the mean arithmetic value, cm; $\Delta_{0.95}$ is the error of the mean (at the probability level of 0.95); and V is the coefficient of variation, %.

and is found deeper (109–139 cm). Gypsum crystals and druses appear in the soil profile from the depth of 2.7 m.

The soil cultivated during the past century (plot 3, pit 191) has a different morphology (Fig. 3; averaged data on the depths of soil horizons are given in Table 6).

Ap (Ha) The plow horizon; dark brown (10YR 4/3); fine crumb structure, with fragments of coprolites; siliceous powdering on ped faces.

B1 (Hpi). The upper part of the transitional horizon; dark yellowish brown (10YR 4/4); angular blocky structure; effervescence is observed in the lower part of the horizon (from the depth of 38 cm).

B2 (Ph(i)k). The lower part of the transitional horizon; dark yellowish brown (10YR 4/4); fine angular blocky structure.

BCca(Pki(h). The carbonate-illuvial horizon; yellow-brown (10YR 6/6); prismatic–blocky structure with shining ped faces; mottles and streaks of humus.

Cca(Pki). A relatively thin horizon with abundant calcareous nodules; yellow (10YR 7/6), with prismatic structure; rather compact. The thickness of this horizon is approximately 2.5 times lower than that in the analogous horizon of southern chernozems.

C (Pk). The loess layer weakly transformed by pedogenesis; yellow color (10YR 8/6).

The soil presumably plowed in the antique time (plot 2, pit 190) consists of the same horizons as those described on plot 3, but their thicknesses (Table 6) and some morphological features are different.

Ap (Ha). The plow horizon with fine crumb structure; dark brown (10YR 4/3).

B1 (Hpe). The upper part of the transitional horizon; dark grayish brown (10YE 3/2), with coarse crumb structure; siliceous powdering on ped faces.

B2 (Ph(i)). The lower part of the transitional horizon; dark brown with yellowish tint (10YR 4/4); prismatic structure is only seen in the lower part of the horizon; the features of illuviation are less distinct than those in the soil of pit 191.

BCca (Pki(h)). The carbonate-illuvial horizon; light brown (10YR 7/4); the line of effervescence is found near the upper boundary of the horizon (at approximately 73 cm); humus streaks are clearly seen against the background color.

Cca (Pki). The horizon with a maximum concentration of calcareous nodules; light brown color (10YR 8/4); compact; with prismatic structure.

C (Pk). Loess; yellow color (10YR 6/6).

This soil has been subjected to agricultural impact for about 350 years, including 250 years in the antique period and 100 years in the recent past. It should be noted that its cultivation in the antique period proceeded under somewhat different climatic conditions. The last two centuries before the Christian era were relatively dry [1]. After them, the climate in the Black Sea region became more humid and somewhat cooler than the modern climate. In the interval from 1600 to 1800 years ago, the mean annual temperatures were 3.6°C lower than those at present, whereas the precipitation was 12% higher [13]. According to our data [11], before the peak of the maximum solar activity (1975 years ago), there was a century with very favorable conditions of soil formation. The growth of soil humus horizons in the studied region in a period from 1900 to 1800 years ago was estimated at 1.3 mm/year (according to the studies on archaeological objects). Thus, despite the fact that the studied soil could be subjected to erosion, the thickness of its humus horizon exceeds that in the recently cultivated soil by 5–6 cm.

The agrogenic evolution of soils can be diagnosed on the basis of data on soil morphology, including the thickness of the humus horizon and the depth of the horizon containing calcareous nodules. In the studied area, the thickness of the humus horizon in the soils cultivated during the antique time is by 9-14% (or by 4–7 cm) greater than that in the virgin soils. In contrast, in the soils that have been plowed during the past century, the thickness of the humus horizon is by 8–12% lower than in the virgin soils. The depth of the horizon with calcareous nodules is rather variable. No definite differences between the soils cultivated in different epochs can be observed with respect to this parameter. The increased depth of the humus horizon in the soils cultivated in the antique time should be considered their relic feature, as these soils have been subjected to the same loads as recently developed soils during the last 100–130 years. In particular, they have been subjected to erosion and deflation. It is interesting that the water infiltration capacity of the soils cultivated in the antique time is 1.4 times higher that of their virgin analogues [22]. This has resulted in a more even coloring of the humus and transitional horizons with humic substances. The soil of plot 3 (cultivation for about 100 years) has been subjected to wind erosion, as its humus horizon is thinner than that of the virgin soil. The erosional loss of the soil material and dehumification processes have led to the transformation of the lower part of the transitional horizon that has partly lost its prismatic structure typical of the dark chestnut soils. In these soils, the dynamics of soil processes has a distinct seasonal pattern dictated by the soil moistening in the winter and spring seasons and the soil drying in the summer and fall seasons. As found by Prasolov [27, p. 269], the thickness of the A + B horizons (or H + Hp + Ph horizons) in the dark chestnut soils varies from 55 to 80 cm and corresponds to the maximum depth of the soil moistening to the level of doubled maximum hygroscopy during the winter and spring seasons. As noted above, the water infiltration capacity in the old-arable soil is increased, and the depth of the soil moistening in this soil is probably greater than that in the virgin soil and in the soil cultivated during the past century. This explains the degradation of the prismatic structure and some loosening of the soil mass in the lower part of the transitional horizon.

As plots 2 and 3 are found relatively close to one another (at a distance of 2.6) and under similar geomorphic conditions and crop rotation systems, we can suppose that the character of the agrogenic evolution of these soils during the last century has been approximately the same. However, the soil that was also cultivated in the antique time has some distinctive features. The upper part of its transitional horizon does not contain solonetzic features, the siliceous powdering on ped faces is more pronounced, and the soil structure and microstructure are better developed. The thickness of the humus horizon in this soil is even greater than that in the virgin soil. If the latter is taken at 100%, the thickness of the humus horizon in the recently cultivated soil comprises 80%; in the soil additionally subjected to cultivation in the antique time, it increases to 112%. Other distinctive features of the soil cultivated in the antique time are the increased depth of the illuvial horizon and the greater depth of carbonates and the horizon with calcareous nodules. In the dark chestnut soils of the studied region, the average depth of the upper boundary of the horizon containing abundant calcareous nodules is 77 cm ($n = 44$) [9]. In the southern chernozems at the same latitude, it reaches 79 cm ($n = 93$). In the soil cultivated during the antique time, it lies at 106 cm (Table 6).

The analysis of morphological features in the considered sequence of agrogenic and virgin soils makes it possible to formulate several important conclusions.

(1) The thickness of the humus horizon and the upper transitional horizon is characterized by the relatively low spatial variability (as judged from the coefficients of variation) and can be used to determine the rate of the humus horizon formation under the impact of agrogenesis. The soils cultivated in the antique time have a deeper humus horizon than the recently cultivated and virgin soils of the region; taking into account recent processes of soil degradation, the difference could reach 16 cm. Thus, the period of soil cultivation in the antique time was characterized by the active growth of the humus horizon (0.6 mm/year). The thickness of the entire humus profile (A + B1 + B2) in the dark chestnut soil cultivated during the antique time corresponded to the values typical of southern chernozems in Ukrainian steppes [24, 28].

(2) The depth of effervescence and the depth of the upper boundary of the horizon with calcareous nodules in the soils cultivated during the antique time are also greater than those in the virgin and recently cultivated soils. The leaching of carbonates could be due to a better soil moistening in the antique time and higher values of the water infiltration capacity in the old-arable soils.

(3) These changes in the soils cultivated during the antique time for about two centuries allow us to classify them as slightly solonetzic deep-humus dark chestnut soils with a lowered boundary of effervescence.

The main factors that control the agrogenic transformation of soils in the steppe zone have been described in several works [2, 15, 16, 18, 22, 25]. In general, they may be formulated as follows. The tilled soil has an increased water infiltration capacity, which favors deeper soil moistening in the spring. The period of water transpiration by crops is shorter than the period of water transpiration by natural steppe grasses. The soil temperature regime becomes more contrasting; the deep and strong drying of the soil mass in the summer is accompanied by the appearance of deep cracks in the humus horizon. In turn, these cracks serve as channels for the rapid downward migration of water during rains in the fall. The permanently dry deep soil layer disappears, and the soil water regime becomes periodically percolative (in the extremely wet years). Overall, the depth of soil moistening increases considerably.

A comparison of data on water reserves in the virgin steppe soil of the Askania Nova Reserve and its cultivated analogue [18] has shown that the total pool of water in the 2-m-deep soil layer is 60 to 80 mm higher in the cultivated soil despite its strong desiccation from the surface in summer. It should be noted that soil cultivation technologies used in the antique time were rather effective from the viewpoint of soil conservation. The topmost soil layer was tilled; deeper, the soil preserved the biogenic vertical pores that also favored deep soil moistening.

It is known that the agricultural development of soil is often accompanied by considerable changes in the soil properties and processes. First of all, the soil climate is transformed. The processes of soil metamorphism and migration of substances are generally accelerated in the cultivated soils. At the same time, the input of organic matter (plant residues) as the source of energy for many soil processes often decreases. As a result, the soil evolution under the impact of long-term cultivation can be referred to as the allopseudomorphosis.

This term is coined from Greek *allos* (other), *pseudes* (false), and *morphe* (shape). It denotes progressive changes in the morphology of long-cultivated soils that are not accompanied by the profound transformation of the soil system at lower levels of its structural organization. Thus, the more active development of the humus horizon and the leaching of carbonates and salts in the long-cultivated soils take place in close relationship with a number of soil degradation processes, including dehumification and deterioration of the soil structure.

Such a specific evolutionary pattern of cultivated soils, including the soils that were cultivated in the antique time, poses the problem of their adequate classification and diagnostics. In particular, this concerns the area of dark chestnut soils in the Ukrainian part of the northern coast of the Black Sea. It is known that southern chernozems are often found within this area. From my point of view, the origin of these soils may be related to the development of soil cultivation in the antique time. Thus, to the east of the Tiligul liman (including the area between the Berezan and Sosik limans), virgin plots are usually occupied by the solonetzic dark chestnut soils. However, in the areas of the long-term soil cultivation, especially during the antique time, these soils have acquired many features typical of southern chernozems.

CONCLUSIONS

Cultivated soils in the area of ancient agriculture on the northern coast of the Black Sea still preserve distinctive features differing them from their virgin analogues. In the antique time, some of them were cultivated for up to 700 years. Afterwards, these soils were abandoned. The new stage of their agricultural development began about 100–130 years ago. At present, despite the strong mechanical impact on the soils in the modern period, the soils cultivated in the antique time differ from the soils that have only been cultivated during the last century. This points to the irreversible character of the agrogenic evolution of soils upon the minimal rates of soil denudation. The soils with agrogenically changed properties carry valuable information on the history of land development. This is particularly true with respect to the soils cultivated during the antique time. Such soils should be included in the Red Data soil book. Their study is important in the context of prediction of the state of soils upon the long-term agricultural use.

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