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SOIL SCIENCE

Evolutionary Trends in the Geochemistry of Steppe Soils under Long-Term Agricultural Use

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Abstract—The aim of this research was to identify long-term changes in the material composition of arable and fallow lands in the agricultural district of an ancient center in the Northern Black Sea region. Geochemical features of changes in the upper mineral soil horizon of different-aged arable and fallow lands near the ancient city of Kerkinitis were studied. The multitemporal boundary between arable lands of different ages was identified, and indicators to diagnose residual signs of former agricultural loads were revealed in the material composition of agrozems using geostatistical methods. The use of such unique objects of study as soils of ancient agricultural areas is related to the potential evaluation of risks of fertility loss because of slow but practically irreversible processes of pedogenesis and the opportunity to prevent or reduce their negative manifestations in arable land.

Keywords: antique farming, continually plowed lands, fallow lands, soil evolution, soil geochemistry
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INTRODUCTION

The increasing use of high-input technologies in current agriculture is impossible without soil-ecological monitoring, including the regular control of parameters ensuring the production process and the health of soil in the rhizosphere zone (nutrients, acidity, humus status, microelements, ballast components of fertilizers and ameliorants, etc.). Such control performed every 5 years (for the main properties and regimes) or every 10 years (for the contents of salts, total macro- and microelements, etc.), as well as stationary observations of changes in the content of humus during several cycles of multicourse crop rotations [1], does not go beyond the short- and medium-term dynamics of pedogenetic processes. Precise farming technologies require studying the spatial variability of agrochemical parameters of soils in their current state [2] without account for the time factor. The integrated use of multidimensional statistics, neural networks, and geoinformation technologies provides new opportunities for simulating the spatial heterogeneity and predicting changes in soil fertility [3–6], including under steppe zone conditions [7].

In recent years, special studies of long-term arable soils revealed a strong transformation of their physical, hydrological, and geochemical properties [8–12]. The specificity of agricultural technologies related to the evolution of farming practices affected the structural and functional organization of soils. The informatory role of long-term arable and long-term fallow soils is determined by the opportunity for predicting evolutionary trends of elementary soil-forming processes in recent soils, where the duration of management can be shorter than the agrarian history of old agricultural regions by 4–5 times. Among the antic poleis of the Northern Black Sea region, a great interest of researchers is attracted to the agricultural region of Kerkinitis (early last third of the fourth century–second century BC) near the city of Yevpatoria (Republic of Crimea).

The aim of this work was to establish the evolutionarily significant (hardly reversible) changes in the material composition of long-term arable soils in the steppe zone under the effect of repeated and long use of lands for crop growing. Objects of study were long-term arable soils in the agricultural region of an antic poleis (Kerkinitis).

EXPERIMENTAL PROCEDURE

The research site to the northwest of Yevpatoria was a trapeziform area of 5454 ha. Within the site, micellar-calcareous medium-loamy southern chernozems on loess-like loams (90 L) and rubbly medium loamy calcareous chernozems on eluvium of calcareous rocks (79 ek) occupy 2743 and 2711 ha, respec-

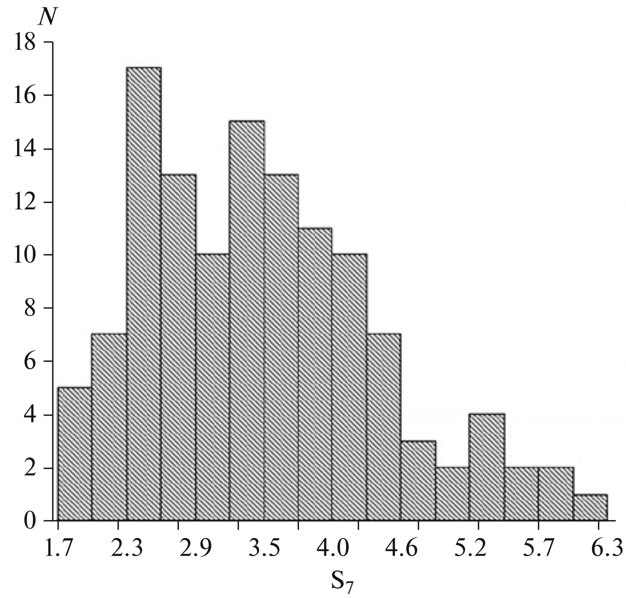

Fig. 1. Frequency distribution histogram of the integrated parameter S_7 values, where *N* is the number of soil sampling points.

tively. The southeastern part of the site, which is close to the city walls and has signs of land management, should enter into its agricultural region. The grid of field survey had lines with a spacing of 0.36 km. However, no survey was performed on old necropolises and in places of former perennial plantations (vineyards, orchards) with ditched soils, according to data from topographic maps of different times and satellite-based images. A total of 128 sampling sites from the upper (0–20-cm) soil layer were selected. In 2015, 20 fields were under fallow.

The Munsell color system was used for the determination of soil colors [13]. Within the color range of dry soil between 10YR 6/4 (light yellowish brown) and 10YR 3/3 (dark brown), 15 main colors were separated, the general direction of whose changes reflected the increase in color lightness (value). The Munsell colors were translated into C_M marks (from 1 to 8 with increasing value and chroma).

From the results of selective determination of soil organic carbon (C_{org}) in samples with different C_M values (n = 13), the relationship between the parameters was calculated

$$C_{\mathrm{org}} = \left(\frac{7.294 - C_{\mathrm{M}}}{29.61}\right)^{-(1/4.679)}, \quad \eta^2 = 0.90,$$

and the diagram of carbon distribution in the soil was plotted for the entire site area.

Concentrations of macro- and microelements in the plow horizons of soils were determined by X-ray fluorescence analysis on a Spectroscan Max-GV. The obtained oxide concentrations were recalculated to the contents of elements. The variation coefficient for 52 tested geochemical ratios and coefficients was used as a criterion for the determination of seven main geochemical parameters suitable for diagnosing residual signs of former agricultural loads in the material composition of agrozems.

Comparative analysis of the results of agrogenically determined evolution in long-term arable soils needs an objective method for discriminating plowlands of different ages on an area. Geostatistical analysis was used in studies of different spatial regularities for the simulation and prediction of changes in soil properties, including on the European scale [6]. Geostatistics proposes a set of tools suitable not only for the simulation of the spatial distribution of parameters under study but also for the mapping of their heterogeneity on different spatial scales [14]. After the normalization of diagnostic parameter values, their spatial distribution was visualized, and the boundary between long-term arable soils (tilled before the mid-20th century, or at least 600 years ago) and recent arable soils (150–165 years) was determined by geostatistical analysis (Spatial Analyst in ArcGIS 9.3).

The combination of seven normalized rasters of soil parameters gave a derivative raster of an integrated soil parameter (S_7). Six parallel profiles with a spacing of 1 km were plotted along the spatial trend of the maximum S_7 variation (from southeast to northwest) using the 3D Analyst module. The method of differential integral curves (DICs) was used to reveal qualitative jumps in the S_7 changes along the profile. For each profile cell, the cumulative sum of the deviations of module coefficients from the mean value over the profile was determined and DIC graph was plotted. The inflection points on the plot corresponding to the maximum DIC values were denoted as S_7 and their mean value was calculated to be 3.34. An isoline for the mean S_7 value was automatically drawn, which denoted the boundary between plowlands of different ages.

RESULTS AND DISCUSSION

The frequency histogram of the integrated parameter S_7 has two distinct maximums indicating the presence of two different subsets, which can be related to the effect of a strong factor: difference in the ages of plowlands (Fig. 1).

The boundary between long-term arable soils (LU-O) and newly plowed soils (LU-N) based on the results of combining seven soil indices (table) by single kriging of spherical model with account for anisotropy (indicator of the direction of spatial data autocorrelation) is shown in Fig. 2. The mean S_7 value for the inflections points was 3.36 ± 0.10. The distances to the inflection points in six profiles were in the range 3.4–4.5 km, with 4.1 km being the average. An isoline corresponding to the mean value of the integrated parameter of soil properties (S_7) was drawn on the raster, which divided the research site into two parts qualitatively differing in the values of selected diagnostic parameters (Fig. 2). The determined boundary between the old agricultural zone of the antic poleis and the region of the current plowed stage passed at 6.4–10 km to the west and northwest of Karantinnyi Cap (Kerkinitis) and at 3–6 km from the Black Sea coast. It divided the research site proportionally to the plowland areas of different ages (48 and 52%).

The plow horizons of soils were characterized by near neutral reaction of soil solution (pH = 6.7–7.0), low humus content (2.6–2.7%), and high contents of available phosphorus (2–4 mg/100 g, Machigin method) and exchangeable potassium (38–41 mg/100 g).

Within the entire site area, the dominant Munsell color for 69% of the soils varied from yellowish-brown (10YR 5/5) to brown (10YR 5/3). The corresponding calculated value of the dominant content of C_{org} was 1.55–1.73%. Despite the narrow variation range of C_{org}, reliable differences between continually plowed land and modern-day plowed land were determined (from LSD_{05}) regardless of their genesis.

Comparative analysis showed that accumulation of Ca, Sr, and Na in the plow horizon due to the longer agrogenesis mainly occurred in the both soil types, as well as accumulation of P and Mg in soils 70 L and Mg and P in soil 79 ek at the simultaneous decrease in the contents of Rb and Ba. No differences in the biological activity and bioproductivity (from the Mn/Al and Mn/Fe ratios) were observed between plowlands of different ages. This is related to the fact that Mn occurs in the form hardly available to plants and its biogenic accumulation is low under these geochemical conditions (its content in fallow lands was 966 ± 27 mg/kg, with a variation coefficient being 13%). The total content of K_2O also little varied under these conditions.

It is known that quartz is one of the most weathering-resistant minerals; its disintegration and entering into fine fractions are possible only after long soil weathering. It should be noted that the content of SiO_2 in long-term arable soils developed on loess-like loams and eluvium of calcareous rocks is lower than in recent soils by 1.4–1.6%. This indicates a deep transformation of the mineral component of long-term arable soils due to agrogenesis. Under fallow conditions, the steppe vegetation favors the compensatory accumulation of SiO_2, which results in an increase in the content of silica compared to long-term arable soils by 3.7% (to 53.3%). Higher concentrations of total phosphorus and easily soluble Na and Mg salts can remain as residual signs in the plow horizon of long-term arable soils, as opposite to recent soils.

Thus, long-term arable soils have lower content of C_{org}, higher content of total seven heavy metals, and higher ratios of easily mobile metals (Ca, Sr, Mg, Na) to Ti and of Rb and Ba to Sr (table). Therefore, agrogenic transformations of the material composition of soils under long agricultural practice, despite their genetic differences, can be estimated as a significant factor favoring the stronger dehumification of the plow horizon (by 10–15 rel %) and higher carbonification (by 47–53%), which stimulates the accumulation of Sr and As.

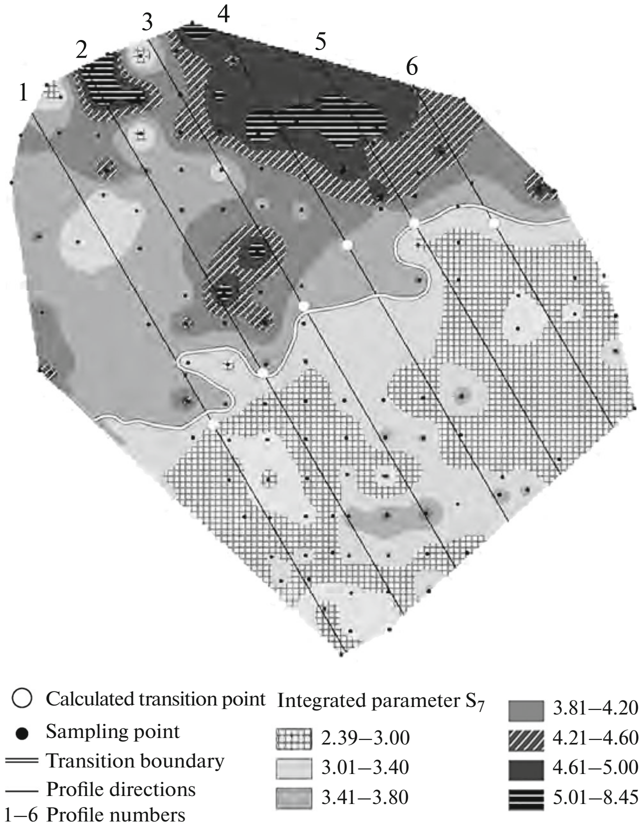

Fig. 2. Boundary for the qualitative transition of soil properties according the geostatistical analysis of spatial distribution of the integrated parameter S_7.

From the results of studying the old agricultural region to the south of antic Olbia [12], the agrogenically controlled evolution of soils under the effect of long agricultural practice can be considered irreversible, because no complete restoration of some physicochemical properties of long-term arable soils (16 centuries) to the level of regional standard was observed even after the long (postantic) fallow conditions.

From the results of cluster analysis with the use of diagnostic parameters (table), long-term arable soils in the agricultural region of Kerkinitis were revealed among all objects with reductive successions (n = 20). The insignificant differences in the content of humus in the 0- to 20-cm horizon (up to 0.03–0.12%) between postantic fallows and long-term arable soils suggest that the manifestation of dehumification is limited, which is reflected in the equilibrium humus

Mean values ($\bar{X} \pm t_{05}S_{\bar{x}}$) of diagnostic geochemical parameters in long-term arable soils (LU-O) and recently plowed soils (LU-N) (the number of determinations is given in parentheses)

Parameter	70 L		79 ek	
	LU-N (31)	LU-O (21)	LU-N (35)	LU-O (41)
C_{org}	1.85 ± 0.1	1.66 ± 0.1*	1.90 ± 0.1	1.61 ± 0.03**
Ba/Sr	6.12 ± 0.7	3.45 ± 0.4**	6.43 ± 0.8	3.83 ± 0.4**
Rb/Sr	0.92 ± 0.1	0.46 ± 0.1**	1.00 ± 0.1	0.54 ± 0.1**
(Fe + Al)/(Ca + Na + Mg)	2.06 ± 0.3	0.99 ± 0.2**	2.32 ± 0.4	1.29 ± 0.2**
(Ca + Na + Mg + Sr)/Ti	184.04 ± 17.6	375.28 ± 49.5**	187.21 ± 30.8	369.33 ± 76.2**
(Ca + Mg + 10P)/Ti	8.91 ± 1.5	19.61 ± 3.5**	8.79 ± 1.8	17.29 ± 3.3**
Σ(Ni, Cr, Cu, Pb, V, Ba, Co)	872.97 ± 16.6	836.39 ± 24.6*	875.37 ± 15.9	840.40 ± 15.8**

* and ** denote significant differences in the geochemical parameters of soils used during different times (LU-N and LU-O) in each genetic group according to LSD_{05} and LSD_{01}, respectively.

content of long-term arable soils (2.76 ± 0.05% under these steppe zone conditions). The potential fertility of plow horizons in long-term arable soils, which can be estimated from the (Ca + Mg + 10P)/Ti ratio, reveals no deep agrogenic degradation, which could be expected because of the observed dehumification (relic exhaustion by plowing, which was not eliminated during the long-term fallow period). The calculation of potential fertility index (FI according to [15], with substitution of SiO_2 with Ti in our modification) showed that its mean value for long-term fallow soils is 1.95 times higher than for modern-day long-term arable soils.

The biogeochemical specificity of long-term fallow soils is manifested in the most efficient renaturation of long-term arable soils by steppe vegetation due to the biogenic accumulation of such elements as Si = Co > K > Cu > Ni (ranked in descending row). The largest losses in these soils (in comparison with long-term arable soils) are observed for the following elements: Ca > Na > Sr > Mg > As.

When stable components of the soil system (like Ti and silica) are used, soil weathering processes due to agrogenesis are easily identified from the content of the main cations removed to soil solutions: Ca and Mg bound to soil calcite and dolomite, Na, Sr, and low-mobile elements (Rb, Ba) (table). The precipitation of Ca and carbonate-associated Sr occurs in the postagrogenic horizon due to the presence of calcareous parent rocks, which act as an alkaline geochemical barrier. Long-term fallow soils are more enriched with micas and potassium feldspars (associated with Rb and Ba) than modern-day arable soils.

Agrogenic transformations are quantitatively expressed in more significant losses of alkali metals from antic arable soils than from modern-day arable soils within the antic agricultural region, as indicated by residual differences (no less than 41–61%) in long-term fallow soils. In addition, despite the geochemical specificity, which hampers the migration of elements, the removal of heavy metals from the current plow horizon of long-term arable soils is more active (by 7%); thus, the relative losses of the elements form the following decreasing series: Pb > V > Co > Cu > Ni > Cr > Ba. The observed regularities are obviously related to the differences in bioclimatic conditions between the former and current agricultural periods. Analysis of numerous paleogeographic data [16] showed that the lifetime of Kerkinitis corresponded to the fresh–wet stage of the centuries-long cycle.

At the updating of the cadastral registration of agricultural lands, it is advisable to keep long-term fallow soils as unique objects of long-term renaturation and candidates to the regional *Red Book* of soils. These objects can include the revealed long-term fallow soils at 2.8–3.2 km from the western bank of the Moinak Lake. From the results of studying the soils of ancient agricultural regions, trends in the agrogenically controlled evolution of steppe soils at the current stage of agrogenesis (no longer than 150–160 years) can be estimated, and a complex of sustainable preventive measures aimed at reproducing soil fertility and preventing risks of above-standard manifestations of soil degradation can be developed.

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