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Soil-genetic differences of multi-aged fallow lands in an ancient agricultural region of steppe Crimea

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Abstract. Since the beginning of the 21st century, the cultivated land located in the European part of Russia decreased, which resulted in the formation of a stable area of young fallows, presented both in forest and steppe zones. In the steppe, any cultivated areas with long agricultural history can open up opportunities for studying fallows in a wider chronological range and for assessing the rates of restoration of soil and plant cover. The aim of the study was to comparatively analyse the soils of fallow lands of different times near the ancient settlement of the NW Crimea and to identify relict and recent evidence of pedogenesis. Having analysed intra-horizon differences in geochemical parameters, it has been revealed that the lower layers of the humus horizon kept in soil memory the evidence of two centuries with a more arid climate (before the 1st c. AD). The indicators of such bioclimatic environment include higher content of Cl, Ca, S, As, P in post-agrogenic horizons. The study of recently ploughed fallows has resulted in the discovery of the phenomenon of heterogeneous horizons which retained agropedogenesis relics from agricultural pre-history (increased share of fulvic acids and content of the above-mentioned elements), but also acquired recent properties in the current bioclimatic environment.

1. Introduction

In many countries, especially in the post-Soviet ones where the cultivated land has sharply decreased since the 1990s [1, 2], the scientists have recently started active examinations of operational features of abandoned agricultural lands (post-agrogenic ecosystems) and the rate of vegetation and soil renaturation [e.g., 2–6]. Such territories as the rural districts around the ancient cities of the Northern Black Sea Region are of particular interest because they can offer an opportunity to study sets of different-time fallows in various soil and climatic conditions and in a wide chronological range. Due to intensive development of survey systems and accumulation of data from multi-temporal satellite observations, it is efficient to diagnose the fallows with the use of remote sensing [7, 8]. To map fallows on large areas it is commonly to use automated methods, for example, SVM (support vector machine) [9], OBIA (object-based image analysis) methods [10], and methods for analysing sets of multi-temporal images [11, 7]. One can use differently detailised images for fallow mapping [12, 13]. Fallows can be identified based on specific properties of their spectral response [14, 15] or structural features. To define the local textural features of the soil cover one can use drone-assisted aerial photographic survey at the periods most suitable for high-quality survey. The use of remote sensing results with geo-referenced sampling opens up new opportunities for characterisation of post-agrogenic ecosystems. Based on the bioclimatic potential of pedogenesis in a specific area, the postagrogenic transformation of soils is largely similar to the natural reproduction of physical, chemical, and biological parameters, which reflect processes with short characteristic times (years – decades) (e.g., [2, 5]). However, relict signs of agrogenesis are found when analysing the results of processes with longer characteristic times. The aim of the study was to analyse the intrahorizontal differences between soils in terms of the qualitative composition of humus, the composition of macroelements and trace elements in a series of fallow lands of different times near a typical ancient settlement of North-western Crimea in order to establish relict and acquired (recent) evidence of pedogenesis in ancient and modern bioclimatic settings.

2. Materials and methodology

2.1. Research objects

The territory with different-time history of land use is located 15 km to the north-east of the ancient Kerkinitis (the present Yevpatoria). The key site is located within a gently undulating plateau covered by grass-wormwood and petrophytous vegetation with islands of grasshopper (*Stipa capillata* L.) subject to moderate cattle grazing load. Background soils are carbonate rubble Chernozem on thin loess loams underlined by eluvium of dense limestone (Petrocalcic Chernozems (WRB)). Autogenic progressive successions began to form as soon as ploughing was abandoned in the ancient period (in the 2nd c. BC) and at different time intervals in the 1980–2000s.

In addition to habitable territories, the archaeological landscapes in the steppe zone contain infrastructural elements (road network, fortification and land management boundaries) [16], which makes it possible to detect the agricultural development areas existed in the ancient times [17]. The research territory included two settlements of Tyumen 3 and 2, which were different in functioning time. The earlier studies [17] have shown that in terms of newly formed humus horizon thickness by pedochronological dating method the settlement of Tyumen 3 can be dated back to the Sabatinovka culture (14–12 centuries BC), when the North–Western Crimea was inhabited by tribes of farmers and cattle herders leading sedentary lifestyle. The results of the magnetic survey conducted at the Late Bronze Age settlement of Tyumen 3 have shown that there is a series of parallel lines matching the boundary ramparts, i.e., the boundaries of the so-called "long fields" that functioned later, in the Early Iron Age [18]. Earlier [17], on the land plot near the Tyumen 2 ancient estate, we determined the topological structure and metric parameters of the land management system for grain growing, which is dated to the middle of the 4th c. BC. The Tyumen 2 estate is adjacent to the land mass that has not been affected by recent ploughing. Here, on aerial photographs, satellite images and even visually you can see traces of "long fields" that extend mainly from northeast to southwest and are confined by the boundary ramparts. The width of the land plots between the main transverse borders of the boundary system varied from 24 to 34 m, with an average value of 29±0.9 m [17]. According to the general northeast to southwest direction of the main boundaries for ancient land use planning (azimuth 210°), we made 6 soil sections with numbers from 65 to 70 and with in-between distances of 515, 839, 351, 294 and 479 m respectively. Using the method of agrogenic soil transformation series, you can compare the properties of virgin soils, different-time arable lands and fallows under homogeneous landscape conditions. In the ancient agricultural areas, it is difficult to justify the unconditional status of a virgin soil analogue even if it is discovered, so a comparison can be made for a series of arable and fallows with different development (reclamation) duration respectively. The objects of the study included multi-temporal fallows as of 2020. Different-year maps show how new plots were drawn into arable land from the south-western part of the land mass up to the location of the ancient estate where there was no farming agriculture in the modern period. After a short-term ploughing (in the 1950–1960s) with some technological criteria restrictions in place they were abandoned. Consequently, according to the remote sensing data the key plots has the following land use history: 65 (post-antique fallow); 67 (1953: arable land; since 1985: fallow): 66 (1960: arable land; since 1985: fallow); 69 and 68 (1973, 1985, 2006–2010, 2019: arable land; abandoned in 2020); 70 (since 1985: arable land; 2012–2018: fallow; 2019: arable land; abandoned in 2020). Near the Late Scythian settlement of Tyumen 2 we studied long-fallow soils with no ploughing evidence in the modern period (since the mid–20th c.), which has been confirmed by pedogenic surveys. We made control section 65 (at the border of the ancient land delimitation area) and section 66 (in the system with longitudinal and transverse boundaries) to the north-east of this settlement and section 67 (in the system of "long fields") to the south-west of the settlement. Thus, a chronological sequence of agrogenic transformations includes the following objects: from the most mature fallow soils to the recent arable ones: 65–67–66 (fallows) – 69–68–70 (arable soils, bastard fallows).

2.2. Research methods
For age estimation of the fallows and ploughing breaks, we used different year's maps, land management plans and remote sensing data. The method of multi-temporal satellite materials analysis was used to diagnose land plots, using structural features, by separate time sections for the period of 1985–2019. The data sources included a series of Landsat TM, ETM+ and OLI images made between 1985 and 2019 (https://earthexplorer.usgs.gov/) and ultra-high spatial resolution images (1 m/pixel) from the Google Earth service for the period of 2006–2019. The Landsat images (with a spatial resolution of 30 m/pixel) were mainly used to assess the condition of the analysed lands between the mid–1980s and the mid–2000s, which were lacking detailed images from the Google Earth service. For long-fallow lands and those subjected to repeated transformations, we used our own method to date fallows with rocky topsoil [19]. This method of field diagnostics of the relative age of fallow lands is based on determining the average value of the subsurface volume of stones from a large sample ($\geq$30 measurements) in a specific area of the fallow lands [19]. Aerial photography of the research territory was carried out at a height of 130 m with the use of DJI Mavic Pro quad copter. This made it possible to construct an orthophotomap and a digital terrain model (DTM) using Agisoft PhotoScan. We used a series of successive ArcGIS transformations to convert the network of potential watercourses into vector format and applied to the resulting layer of linear features the Line Density tool that can calculate the density of multilinear objects falling within the radius around each cell. Using the interactive supervised classification of the orthophotomap, we constructed a raster for projective vegetation cover.

The agrochemical soil parameters (organic matter, total nitrogen, cation exchange capacity, water pH, NPK) were obtained in an accredited laboratory using the methods approved by the national standards. Alkaline hydrolysable nitrogen was calculated by Cornfield, exchangeable potassium and mobile phosphorus by the Machigin method as modified by the Central Agrochemical Research Institute for Agriculture Support. The humus fractionation results obtained by the Ponomareva-Plotnikova method as modified in 1968 [20] can be considered as part of the pedohumus method for reconstruction of soil formation factors [21]. The index of mobility degree for seven-fraction system of humic substances (Kmh) was calculated according to the Kononova and Alexandrova formula [22] using the ratio of the sum of three most mobile fractions of humic (HA) and fulvic acids (FA), i.e. (HA1, FA1, FA1a), to the sum of the remaining four fractions. Soil colour (dry) were described using the Munsell-System [23]. The method of X–ray fluorescence analysis was used to determine the content of main oxides and chemical elements (ppm (mg kg^{-1})). The system of biogeochemical indicators, which showed its informative value for studying a number of agrogenic soil changes in the Steppe Crimea [24] included leaching and bioaccumulation degree estimates The mobility coefficient (Kms) proposed by the authors for these bioclimatic conditions takes into account the ratio of the concentrations of the most mobile chemical elements in relation to silicon oxide and is calculated as: $Kms = (CaO+Na_2O+MgO+Sr)/SiO_2$.

3. Results and Discussion
An analysis of the density raster of potential watercourses clearly demonstrated the relationship between fluvial flow path and land surveying system. In particular, the areas with the lowest density of potential watercourses coincide with the axial zones of boundary ramparts. This is demonstrated by a fallow site fragment with traces of ancient land management to the southwest of the settlement of Tyumen 2 where we made section 67 (figure 1).

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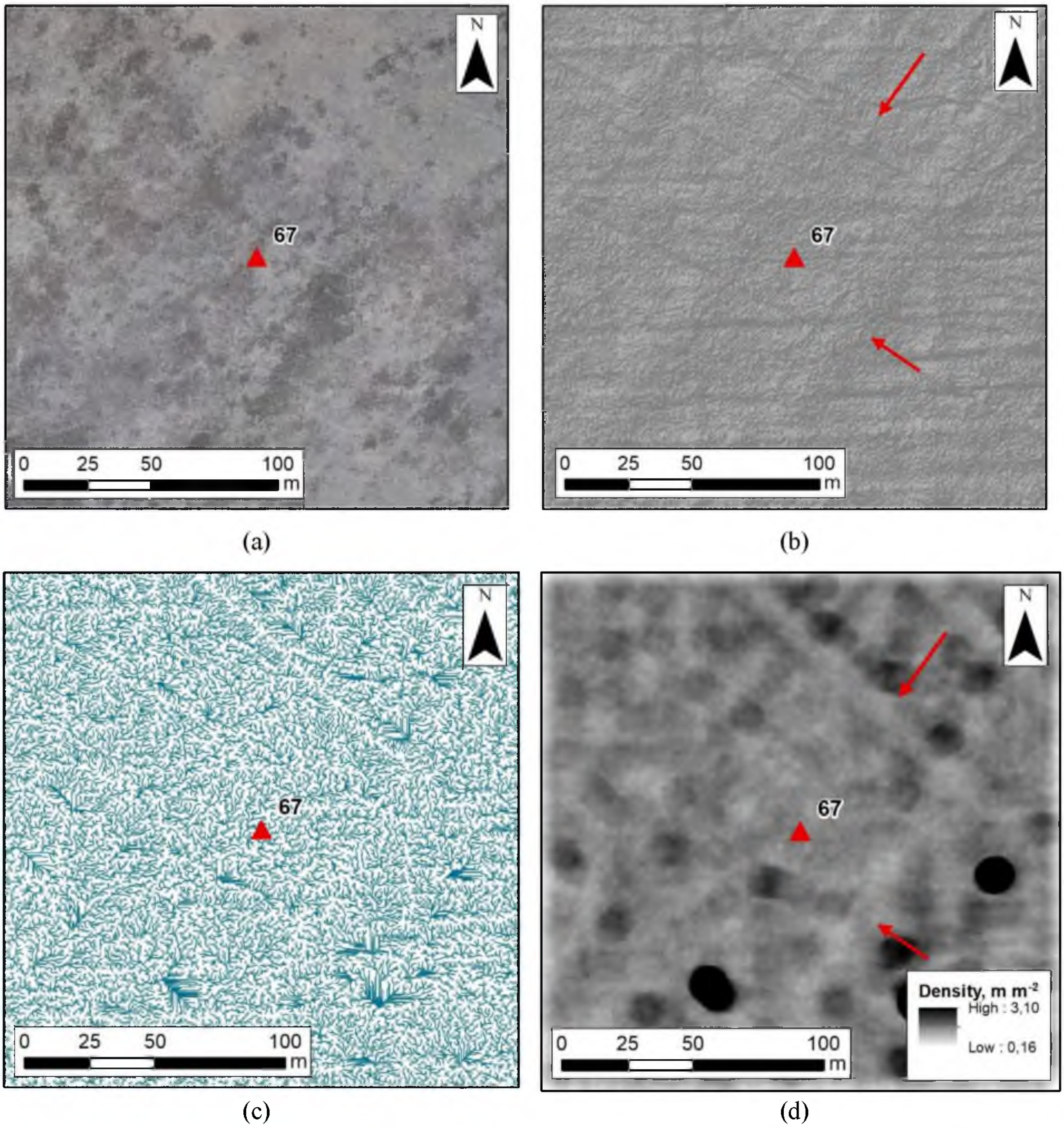

Figure 1. Visualization of the process of constructing a raster of potential watercourses density. Key: (a) orthophotomap, (b) digital terrain model; (c) a discrete raster of potential erosion network based on a raster of the total flow into each cell by the sum of weights for all cells flowing into each cell located down the slope; (d) a density raster of the potential erosion network based on the discrete raster of potential erosional network. Arrows indicate boundary ramparts.

The patterns of water mass movement are completely determined by the ancient land management boundaries oriented from northeast to southwest in the form of boundary ramparts of up to 15 cm high, which have survived until today. The land management infrastructure formed by ancient farmers led to the fact that the original geomorphological surface became discrete, especially with orthogonal land surveying, as, for example, at plot 67. In the dry steppe, the ancient land management boundaries are most effectively phytoindicated in May, when there is active vegetation of wormwood (*Artemisia* *taurica*) on the tops of the ramparts and some grass plants (species of the genera *Festuca* and *Stipa*) and feather grass) are growing on micro-slopes and in depressions. The projective vegetation cover raster obtained during orthophotomap processing allowed us to determine the areas with the most mature associations as of September 25, since *Stipa capillata* bears fruit in August–September. The participation of feather grass in the plant community indicates a long-term autogenous succession regime.To determine the soil depth by backward calculation for a certain period, it is possible to use the pedochronological dating method based on regional relationship between humus horizon thickness and time [25]. After the destruction of the Tyumen 2 ancient estate in the second half of the 2nd c. BC and up to the present time soil could form on any fresh parent rock to the depth of 35–36 cm. "Soil-by-soil" development, that is, applicative pedogenesis tends to run rapidly. A set of statistical data obtained on soil morphology from the territory of the settlement has shown that the average thickness of the newly formed horizon A is 22.6 cm. Therefore, the lower boundary of the upper part of horizon A was determined for each section individually, and the soil samples were taken in the second layer of horizon A from 20–22 (on fallows) to 21–29 cm (on arable land) deep. The upper horizons of fallow and arable soils have small differences in terms of key physical and chemical parameters (Table 1). The fallow soils were more active to accumulate total nitrogen forms, while due to fertilisation the arable soils have an average content of mobile phosphates and a slight decrease in cation exchange capacity. This parameter is most important for section 66 fallow soil that, as will be shown later, is also characterised by maximum mobility of humus substances, being only inferior to section 70 arable soil. The colour of the renaturation layer in fallow soils is brown while it tends to lighten by one Chroma shading (dark yellowish brown) because of ploughing. This correlates with soil differences in organic matter accumulation.

Table 1. Main agrochemical indicators of the upper part of horizon A in fallow lands of different times.

Site No.[a]	Depth (cm)	Munsell colour (10YR)	pH (H_2O)	Nah (mg kg^{-1})[b]	P_2O_5 (mg kg^{-1})	K_2O (mg kg^{-1})	N total (%)	C:N	CEC (cmol(+) kg^{-1})[c]
65	3–17	4/3	8.3	133	8	328	0.22	8.9	27.4
67	2–17	5/3.5	8.3	112	10	341	0.15	10	27.6
66	1,5–15	4/3	8.3	133	8	352	0.23	8.8	31.6
69	0–17	4/3.5	8.3	105	11	232	0.17	8.2	26.6
68	0–17	5/3.5	8.2	133	26	357	0.19	9.4	29.2
70	0–17	4/4	8.3	105	15	329	0.15	9.7	26.4

Note: [a]The sequence of site in the column corresponds to the chronosequence of fallow lands (from more mature fallow to recent arable land); [b] Alkaline hydrolysable nitrogen; [c] Soil cation exchange.

Horizon A of different-time fallow soils contains 1.66 % Corg on average while it is 1.6 times less in ploughing horizons. However, the analysis of humus fractional composition in the agrogenic series of soils (table 2) suggests a more complex pattern of organic matter qualitative transformation.

A longer period of renaturation of steppe ecosystems results in some changes in the qualitative composition of soil organic matter. According to the results of correlation analysis of agrogenic soil parameters, with increasing duration of fallow status the horizon A upper part of carbonate chernozems (0–17 cm) is characterised by increased proportion of fulvic acids, especially, due to the fractions that are associated with fractions 1 and 2 of humic acids, and decreased proportion of humic acids, particularly, because of the faction that is mainly related to calcium, and aggressive fractions of fulvic acids (free and sesquioxide bound). Accordingly, the common pattern for transformation of humus qualitative composition is that if arable soils have a purely humate type of humus in the current bioclimatic conditions then humate and fulvate-humate type of humus (according to the diagnosis on the scale [26]) can be observed in different-time fallow soils.

Table 2. Fractional composition of humus in the upper part of horizon A in fallow lands of different times.

Site No.	Corg (%)	Humic acid (HA), %				Fulvic acid (FA), %					Chumin, %	C_{HA}:C_{FA}	Kmh
		1	2	3	∑	1a	1	2	3	∑			
65	1.45	2.9	14.5	12.9	30.3	2.7	5.4	12.6	12.9	33.6	36.1	0.9	0.21
67	1.52	2.9	14.5	11.0	28.4	2.4	3.5	9.7	5.5	21.1	50.5	1.3	0.21
66	1.73	2.6	16.8	11.1	30.5	2.9	2.9	12.4	5.5	23.7	45.8	1.3	0.18
69	1.10	3.4	20.5	9.8	33.7	3.8	2.5	8.3	3.3	17.9	48.4	1.9	0.23
68	1.96	2.3	19.0	9.8	31.1	2.9	3.4	8.3	4.9	19.5	49.4	1.6	0.21
70	0.93	3.3	27.8	14.2	45.3	4.2	2.3	8.4	6.5	21.4	33.3	2.1	0.17

For various reasons the horizon A topsoils from section 65 and section 70 take the lead in terms of total most mobile fractions (HA1, FA1, FA1a) included in the numerator of the Kmh formula. The post-ancient fallow (section 65) is characterised by the highest content of the FA1 fraction related to the HA1 fraction whereas the current arable land (section 70) is maximally enriched with "aggressive" fraction FA1a. We have earlier come to an important conclusion that at a depth of more than 10–15 cm the organic matter (OM) is mainly represented by ancient humus forms rather than contemporary ones, and if there is a high proportion of fulvic acids noted in deeper horizons this is not an indication of their migration but an evidence of specific features of plant residues humification in the previous historical periods [27]. The post-ancient fallow (section 65) in the layer of 3 to 17 cm is characterised by the highest proportion of fulvic acids (table 2), which is unusual in an alkaline environment (with pH (H_2O) values of 8.3), and may be a reflection of different than nowadays conditions of pedogenesis in the post-antique period, as well as by the highest proportion of humic acid fraction among fallow soils, which is associated with clay fraction and stable sesquioxides. The final stage of economic activity in the settlement Tyumen 2 is associated with the climatic period that is thoroughly studied by various palaeogeographic methods; this period began with humidification reduction starting from the 3rd c. BC and continued with the emergence of a hot, dry climate until the period between the end of the 2nd c. and the beginning of the 1st c. BC [28]. The ratio of Kms values calculated for the upper and lower parts of horizon A from data (table 3) can give an idea of both the maturity degree of fallow soils and the agrogenic transformation of arable soils. Renaturation processes were most effective for the soils from sections 66 and 65 as well as for arable soil, but with two periods of fallow status in the early 2000s and in 2012–2018) (section 69). The fallow soil that was ploughed in the 1950s (section 67) has no signs of differentiation in horizon A. The arable soils from section 70 as well as the arable soils from section 68, which started to be ploughed earlier than from soil section 69, are most turbated based on geochemical characteristics.

A comparison of the biogeochemical features of the upper layer of horizon A for six objects (Table 3) has shown that the sum of soil accumulated elements (P, Ca, K, Mg, Mn, and Cu) is closely related to the content of macroelements required for plants (the value of Spearman's coefficient is 0.97). The total content of plant-essential trace elements (Mn, Fe, Ni, Cu, and Zn) in the surface layer of horizon A is 6 % less in recent fallows than in fallows with a longer period of renaturation. According to Table 3, the lower layers of horizon A in the fallow soils (sections 65–67) are characterised by a higher content of all elements and oxides as compared to the arable soils (sections 68–70), by 1.5 times on average. In particular, the post-agrogenic layers of the fallow soils are significantly enriched (above the average level): Sr, As, P_2O_5, Cu, Cr, S, K_2O, Na_2O, Cl, Fe_2O_3, and Zn. A comparison of the ratios of chemical elements concentrations in the lower and upper part of horizon A for all objects has shown that the differences are subject to higher relative content (> 1) of an assemblage of elements and oxides (in a ranked ascending order: $Sr<TiO_2<Cr<As<CaO<Na_2O<Cu<Cl$), and a lower content, which reflects a descending series:

$$Fe_2O_3>Zr>Ni>Al_2O_3>Ba>V>SiO_2>MgO>Zn>K_2O>Rb>P_2O_5>MnO>S>Pb.$$

Table 3. Geochemical features in the content of macroelements and trace elements in horizon A (layers of renaturation (arable) and through the slash underlying layer).

Element, oxide	Units	65	67	66	68	69	70
CaO	%	17.1/18.6	16.4/16.7	11.6/14.4	15.4/15.7	16.3/16.8	17.7/18.1
SiO_2	%	44.5/41.7	45.6/45.8	50.7/47.5	46.8/46.6	45.5/45.1	44.5/44.3
Al_2O_3	%	9.0/8.3	9.0/9.1	10.7/10.0	9.3/9.6	9.4/9.4	8.9/9.0
Fe_2O_3	%	3.5/3.4	3.5/3.6	4.2/4.0	3.5/3.7	3.5/3.6	3.3/3.4
MgO	%	1.4/1.2	1.5/1.6	1.7/1.6	1.5/1.5	1.5/1.5	1.6/1.6
P_2O_5	%	0.2/0.3	0.2/0.2	0.2/0.2	0.2/0.2	0.2/0.2	0.2/0.2
K_2O	%	1.5/1.4	1.5/1.4	1.6/1.5	1.5/1.4	1.4/1.4	1.4/1.3
Na_2O	%	1.5/1.5	1.2/1.3	1.2/1.2	1.4/0.9	1.1/1.2	1.2/1.7
S	%	0.12/0.13	0.09/0.08	0.09/0.07	1.09/0.09	0.09/0.08	0.10/0.09
Ba	ppm	530/501	546/541	513/474	553/554	549/567	510/517
Sr	ppm	278/265	204/195	156/170	167/162	161/156	176/189
Zr	ppm	200/187	193/197	209/193	211/216	207/204	180/194
V	ppm	80.7/79.0	83.8/81.0	98.6/84.8	84.1/88.2	81.1/83.0	78.5/78.9
Cr	ppm	80.4/76.0	78.1/88.4	85.4/93.4	84.6/84.5	81.9/79.8	79.0/76.5
Zn	ppm	65.5/63.0	63.1/61.2	74.0/66.4	63.8/63.7	61.4/60.0	60.5/61.7
Cl	ppm	53.1/111	59.5/65.2	55.2/58.0	62.5/78.4	67.2/59.7	88.0/89.9
Rb	ppm	55.6/49.0	54.2/54.5	70.9/60.0	59.0/60.3	57.3/56.1	54.5/55.3
Ni	ppm	38.5/35.6	38.2/38.3	42.6/40.3	41.3/41.8	39.6/39.9	36.1/37.4
Cu	ppm	34.7/40.0	28.6/37.7	20.5/28.1	27.5/25.5	26.4/33.4	34.0/36.9
Pb	ppm	21.4/15.0	20.1/11.6	18.3/9.6	18.6/14.8	20.9/17.5	17.0/13.0
As	ppm	22.1/23.7	14.5/18.2	16.3/16.0	15.7/15.6	15.6/16.0	14.6/16.3
Kms	–	0.10/0.11	0.10/0.10	0.07/0.09	0.09/0.08	0.09/0.10	0.11/0.11

Note. Differences between the layers for all objects were not revealed for TiO_2 and MnO.

When comparing the fallow soils (sections 65–66) with the arable ones (sections 68–70) separately, higher values of intra-profile parameter ratio were obtained for such elements and oxides as Cl, P_2O_5, CaO, Cr, and As. The above-mentioned results make it possible for us to conclude that some evidences of the Late Scythian stage of agricultural history when the climate was being more arid have been kept in soil memory of lower layers of horizon A (19–22 cm) of carbonate chernozems with medium-alkaline soil solution characteristics when it is difficult to ensure profile-based migration mobility. In this regard, it is noteworthy that the fallow soil renaturation layer (from 2 to 17 cm) representing the pedogenesis conditions in the current bioclimatic environment differs from the arable soil upper layer in depleted chlorine and calcium oxide with higher concentrations being noted only for strontium and arsenic. The obtained data on the geochemical features of post-antique long-term fallow land are confirmed in the summary of palaeogeographic and archaeological data. The final stage of economic activity in the settlement of Tyumen 2 falls on the late Hellenistic stage of the ancient history of the Northern Black Sea Region, which was characterised by the two centuries (before the 1st c. AD) dominance of hot arid climate and agricultural decline [28].

The extreme members of the agrogenic series of soils are characterised by geochemical proximity of subhorizons in terms of average ratio values for the content of 23 macroelements and trace elements in the lower and upper parts of horizon A. As for the soil from section 70 this is due to systematic soil overturning, and in case of the most mature of the fallow soils (section 65) it is caused by bridging the differences between renaturation layer and post-agrogenic layer. At the same time, the post-agrogenic layer of long-fallow (post-ancient) soil is characterised by 19 to 54 % higher content of As, Sr, S and Cl and total phosphorus as compared to the current ploughing horizon. The geochemical features of the post-antique long-term fallow land noted above indicate that at the final stage of agricultural activity the climate was more arid in this region than the current one (steppe and moderately hot: annual precipitation is 358 mm, sum of temperatures for the period with a temperature of +10 °C is 3,300–3,600 according to the Yevpatoria weather station).

4. Conclusion

Since the ploughing horizon was thin in the steppe zone and even later (until the 1940s) they ploughed to a depth of maximum from 16 to 18 cm due to the limited capabilities of the agricultural technologies used in ancient times, the long-fallow soils have preserved biogeochemical differentiation of humus-accumulative horizon (horizon A). Episodic conversion of post-ancient fallows into arable land with the cultivation depth of 18 to 22 cm (from 1945 to 1954) and 25 to 27 cm (from 1960 to 1965) followed by their abandonment led to the formation of specific post-agrogenic horizons that have largely preserved some evidences of ancient pedogenesis conditions. This was primarily resulted in enrichment of post-agrogenic horizons with chlorine as well as with sulphur, calcium, arsenic and phosphorus. Thus, for the recently ploughed fallows in the ancient agricultural areas we have revealed the phenomenon of heterogeneous horizons that include both recent properties obtained during the renaturation of the upper part of the humus-accumulative horizon in the current bioclimatic environment and relict agropedogenesis signs acquired as a result of centuries-long economic activity.

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