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Assessment of Biogeochemical Soil Variability using a Geo-statistical Approach: A Case Study in the Steppe Crimea

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Abstract: Soil monitoring within the lands of steppe zone (first few centuries) being currently under development makes it impossible to identify the effects of agrogenic evolution symptoms for material composition of the soils. Therefore, the areas with centuries-long agriculture are of great research interest, which include steppe soils at the northern Black Sea coast in the ancient period of Greek colonization of land. The present study aimed to develop an approach to simulation of the spatial variability of soil quality (SQ) using geo-statistical modeling. The raster models of continuous distribution of soil quality parameters, which have been developed using modules Spatial Analyst, and Geo-statistical Analyst have established soils qualitative differences with due account for the length of their treatment, source of potential nutrients for plants and specificity of parent rocks. We have fixed the land boundaries, which differ in farming duration using different ensembles of chemical elements with the same procedures geo-statistical analysis of the spatial variability of three types of indicators of the soil quality. A methodical approach to the identification of agricultural areas with different duration and biogeochemical transformation of soils, which the authors have proposed in this article, uses objective geo-statistical analysis procedures and has the ability to analyse in-depth patterns previously unavailable in research. This makes it possible to recommend this approach for use in the interpretation of soil-ecological monitoring data in ancient land areas with complex soil cover and history of land use.

Keywords: Soil ecology, Biogeochemistry, Soil quality, Long-term agriculture, Geo-statistical modeling

The distribution of scattered elements in the pedosphere, the biological cycle of chemical elements, the role of macro-elements and trace elements in plant nutrition, physiological and biogeochemical aspects of metabolism trace elements and their sources in plant organisms are of great importance in the development of modern geochemical ecology. The soil and ecological monitoring of agricultural land allows assessing and controlling the state of the soil cover, to forecast possible changes in the soil based on an ensemble of sensory indicators of fertility with the focus on fertilizer elements. But such monitoring for long-term exploited soils should be supplemented by periodic diagnostics of trace elements deficiency in agricultural lands and its correction by adding micronutrients to compensate for the loss of the most rapidly consumed trace elements is required (Zelenskaya et al 2018). Steppe ecosystems of East-European plain during the Holocene history were about 4500 years under anthropogenic load of varying intensity (Lisetskii and Pichura 2016). However, the most significant transformation of soils occurred during their agricultural development. This is reflected in the properties of fallow lands (Lisetskii et al 2012) and, in particular, in the change of trace elements (Lisetskii et al 2016, Zelenskaya et al 2018). Effects of long-term agriculture on soil properties studied in various aspects (Saiz et al 2016, Sandor and Homburg 2017, Borisov et al 2018, Chernysheva et al 2018, Gollany and Venterea 2018). Multidisciplinary investigations of the soil agrogenesis influenced by ancient arable agriculture require the search for research objects that are rare in safety (ancient terraces, land plots with preserved borders, etc.) (Homburg and Sandor 2011, Korobov and Borisov 2013, Lisetskii et al 2016).

The objects of the study that differ in agrogenesis duration must have similarity in the type of parent rock, mineralogical and granulometric composition (Lisetskii and Chepelev 2014). To conduct a comparative analysis of the results of the agrogenic-related soil evolution, which differ in the duration of farming it is necessary to solve the key problem – to use an objective method to delimit multi-temporal arable lands. In this regard, the agricultural district (*chora)* of Kerkinitis in ancient Crimea is of great research interest among ancient policies the northern Black Sea coast. The ancient Greek polis Kerkinitis was located on the site of the modern city of Yevpatoriya. An agrarian district was directly adjacent to the city and it was characterized by land division into plots with its own characteristics, which distinguished it from other *chora* delimitation and in particular from *chora* of Tauric Chersonesos.

The ideas about the size of the agricultural district Kerkinitis, which have developed up to date, are contradictory. At an early stage (from the second half 6 c. BC to mid 4 c. BC) the *chora* Kerkinitis was localized near the city, but it is assumed (Scheglov1984) thatin4–2 c. BC the already vast rural district was divided into allotments. Kutajsov (1990),which summarized the views of Wąnsowicz(1974) and Shcheglov(1978), noted that the *chora* Kerkinitis occupied the space of the Black Sea coast not only in the Western but also in the Eastern direction within a radius of about 3 km from the walls of Kerkinitis. However, the coastal strip of 1-1.5 km wide within which there are saline soils is probably not included in the agricultural zone. It is also important to note that the water level of the Black Sea near what is now Yevpatoriya was -2 m in the mid-1st millennium BC and therefore the coastline might have been located 50-100 m offshore from the present one (Kutaisov and Smekalova 2016). The agricultural zone of the policy, as previously thought (Kutajsov 1990), extended to watersheds with fertile steppe soils by no more than 2.5–3.0 km, and the cultivated area could be about 1300–1400 ha. However, in the follow-up works (Kutajsov 2004) this statement was revised: The Kerkinitis county could cover about 80–90 km^2 and ran as a strip of up to 7 km wide along the Black Sea for 65 km. Only arable lands for the main crops (wheat and barley) could occupy 5050–5519 hectares (Kutajsov 2013).

The specific features of the ancient agricultural technologies which have changed for a long time are reflected in the structural and functional pattern of the modern arable soils (we will call them as old-arable ones). Periodic plowing of the same plots with rest periods have largely modelled the future agricultural practices, which are summarized, and we can call them as conservation agriculture (Bitew and Abera 2019); what is important for maintaining of a soil health. The information role of old-arable and long-fallow soils (without the current period of agriculture) is determined by possible diagnostics of evolutionarily significant changes in the material composition of soils as a reflection of the accumulated effects of agricultural practices of the past. Ge-ostatistics methods have become widely used in environmental science (Webster and Oliver 2007, Pelletier and Dutilleul 2018, Ver Hoef 2018, Lu et al 2019, Ghorbanzadeh et al 2019). They are promising for soil cover research. A new method has recently appeared to solve visualization problems, geo-statistical modeling and simulation of the spatial variability of soil (Heuvelink and Webster 2001, Bourennane et al 2003, Paterson et al 2018, Paul et al 2019, Hou et al 2019, Iticha and Takele 2019). The present study aimed to develop an approach to simulation of the spatial variability of soil quality for lands with different farming times in the Steppe Crimea using geo-statistical modeling.

MATERIAL AND METHODS

Lands to the north-west of Yevpatoriya is a part of the Crimean southern steppe agropedological province with plains wavy landscape with heights from 5 m a.s.l. (in the south) to 35 m a.s.l. (in the north). Among the parent rocks loess and residual carbonate rocks dominate. The study site was chosen for the comparative analysis of soils in such a way as to cover both the proposed area of ancient agriculture and the more remote areas with the same types of soil which were certainly a part of the area of the current (150–165 years) agricultural development. Thus, when arranging field studies we initially assumed the existence of qualitative heterogeneity of soil properties, first of all, quite conservative components of the material composition, which could preserve some evidences of the agriculture prehistory in the form of relict features. The field studies were carried out on the site with an area of 5.4 thousand hectares (Fig. 1A) which is located northwest of Yevpatoriya. The field-testing mesh had the size of 560 m. The use of topographic maps of different years and archival satellite images allowed determining10 arrays of vineyards and gardens on the territory of the field test site (Fig. 1A). Within these areas where deep tillage, including plantation ploughing, was probably used no testing was carried out. We also avoided ancient necropolises (over 30 kurgans marked on maps) and areas with anthropogenic disturbances (pits and clusters of stones). We also excluded the areas with modern buildings. As a result, we determined the location of 127 points of soil samples on the arable land, which was promising for the cultivation of grain crops. In the field, there were occasionally short-term (1–5 years) deposits in the fields of rotation, which were included in the sampling. However, any old deposits (n=6) were excluded from the analysis. The modern methods of satellite images interpretation (Smekalova and Terekhin 2018) have allowed establishing traces of ancient land management, which include the boundaries of both lands and plots within them.

Soil samples were taken from a layer of 3–10 cm. For each sample, the soil colour and the content of macro-elements and trace elements were determined. Chemical analyses of soils included the following standard procedures: the organic matter (OM) after Tyurin; the pH values (H_2O) were determined by a potentiometric method; the content of mobile phosphorus and exchange potassium after Machigin. Colours (dry) were described using the Munsell-System (Munsell 2000). Wavelength-dispersion X-ray fluorescence spectrometer was used to determine the contents of chemical elements. Concentrations of macro-elements and trace elements in soils (18 metals and oxides) were determined by the technique of measuring metal mass fraction and oxides in powdered samples. The resulting oxide concentrations were recalculated for the content of elements.

For 121 soil samples, we have developed a database on organic carbon content (Corg), 18 chemical elements and by integrated indicators of soil quality regarding the content of nutritional elements for plants, accumulation of chemical elements in the soil relative to the rock and geochemical "plowed-out" soils. The values of the content of chemical elements were standardized for comparability according to the formula.

$$x_{norm} = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad ....(1)$$

Soil quality (SQ) indicators were calculated using normalized values (1)

$$SQ = (x_1 \times x_2 \times ... \times x_n)^{1/n} \quad ....(2)$$

Where x_1, x_2 ... x_n are the normalized values of the content of chemical elements.

An integrated soil quality (SQ) assessment characterizes soil quality differences with due account for the duration of their treatment, source of potential nutrients for plants and parent rock specificity. Therefore, to show spatial differences in soil cover different lists of elements were used. The SQ1 indicator is calculated by the content of nutrients for plants (Corg, P, Mn, Cu, Ni, Zn, V, Co, Cr, Sr, Ti, Ca, K, Mg, Fe and Si) which have been determined by consolidation of special works on this problem (Kovda 1985, Protasova and Kopayeva 1985, Orlov and Bezuglova 2000, Dobrovolskiy 2003, Kiriluk 2006, Mengel 2008, Bityutsky 2011).The SQ2 indicator reflects accumulation of chemical elements in the soil relative to the parent rock (Perelman, 1989, Dobrovolskiy 2003, Lisetskii et al., 2016). In this case, formula (2) included as a parameter x_i the coefficient of soil accumulation: KS(i)=Si/Pi. A list of elements (i) for soils(S) and for two types of parent rock (P) has been determined by the value of KS(i) >1:

– for soils on loess-type rocks: Corg, P, K, Cu, Mn, Si, As;

– for soils on carbonate rocks: Corg, Cu, Co, K, Mn, P, Si, Al, Ti, Pb, Fe, Ni, Zn.

The SQ3 indicator characterizes biogeochemically "ploughed-out" soils as it has been determined by the ratio of actually recorded concentrations of chemical elements in arable and virgin soils on two types of parent rock:

– for soils on loess-type rocks: Corg, Ti, Al, Mn, Fe, Si, K, Co, Ni, Cu, Zn, Pb, Zr, Rb, Ba, Cr, V;

– for soils on carbonate rocks: Corg, Mn, P, K, Ni, Cu, Pb, Rb, Ba, V.

To visualize the results obtained raster models of spatial distribution of soil properties for the three above indicators were developed. Mapping was done using geoinformational software ArcGIS 10.5 and modules “Spatial Analyst” и “Geo-statistical Analyst”. A vector layer was created with the use of the coordinates of 121 selection points; its attribute base was filled with calculated indicators SQ1, SQ2, SQ3. A deterministic method of inverse distance weighted was used to interpolate the data. The parameters of the interpolation model were chosen in such a way as to minimize standard deviation of interpolated values. As a result, we obtained raster models of continuous distribution for soil quality indicators. The values of indicators SQ1-SQ3 were ranked using equal intervals because their distribution is close to normal.

RESULTS AND DISCUSSION

The watersheds of the steppe are represented by southern carbonate black soils on loess clays and loams (codes on the soil map 70L, 71L, 88L). In the north-west and south-east of the field test site there are carbonate crushed black soils on eluvium carbonate rocks (code 79ek). Arable soil horizons are generally characterized by close to neutral reaction of the soil solution (pH=6.8–7.0), low humus content (2.6–2.7%), high content (by Machigin) of mobile phosphorus (0.2–0.4 mg kg^{-1}) and exchangeable potassium (3.8–4.1 mg kg^{-1}).The land use and management practices have evolved over a long period of time in the rural area of Kerkinitis. After the initial period of Greek colonization when land resources were in excess which allowed the use of fallow farming system, there came the stage of regulated land use related with consolidation of land plots among civil population. This stage came from the turn of the third–fourth quarter of 4 c. BC thanks to the transfer of land management traditions of from Tauric Chersonesos (Kutajsov 2013). The values of soil quality which characterize the concentration of the most important 16 nutrients for plants (SQ1) are most widely represented in the area with values SQ1 = 0.31-0.40 (Fig. 1, B). This area contains traces of land surveying which in ancient times undoubtedly represented a continuous zone of regulated land management in the centre of the field test site but not a set of fragments as in Fig. 1, A. Land plots of square shape were limited by dividing ditches (Kolesnikov and Jacenko 1999, p. 307-309), and strictly regular planning composition of land management is related with the Chersonesean stage of land use in 4-2 c. BC when plots had a crop rotation: steam–winter crops–spring crops (Kutajsov 2013). The central zone of the research area is used to characterize the result of centuries-old agriculture, which basically levelled the initial soil-genetic differences in the territory (soils on loess and carbonate eluvium). However, the previously detected traces of earlier irregular land management within *chora* of Kerkinitis (from the second half of 6 c. to the middle of 4 c. BC) as well as the assumed existence of a complex agricultural system at the initial stage of development (Kutajsov 2013) make it possible to suggest that lands located directly at the city walls were used less efficiently or for a short time for crop production. A complex agricultural system which was used in 6 c. BC and to the middle of4 c. BC in the near *chora* Kerkinitis seemed to be not involved in the consolidation of land boundaries. The lands in the area to the northwest of the city being less fertile according to the SQ1 0.36-0.32 and lower (**Fig.** 1, B) estimates appeared to have been in the later Chersonesean stage of land use being predominantly used for grazing. The ethnographic data indicate to the usual practice of allocating a buffer zone of land between the settlement and the arable land for regular grazing of livestock. Previously, the authors (Buryak and Poletaev 2019) were able to justify the assumed ancient land boundary of the rural area (in 6 km to NW from Kerkinitis (**Fig.** 1, A)) based on geochemical properties of soils with the use of methods of geostatistics and geoinformation analysis. An analysis of the map of distribution probability of multi-temporal boundaries of the arable land has allowed to identify the border of two agricultural zones which according toFig. 1, B is close to the location of the south-eastern boundary of the isoline SQ1=0.36. However, according to the spatial distribution of SQ1 values we have identified three zones on the territory of the field test site: two areas of the least agrogenic amended soils (in the north-west of the field test site and in the south-east (with rare saved land marking)) and the wide central strip with nearly continuous belt of demarcated land and reflection of biogeochemical progradation soil according to the values of SQ1.

Taking into account soil-genetic differences the Fig. 1, C shows the features of selective accumulation of chemical elements in the soil in relation to parent rock (for loess by seven chemical elements, for carbonate eluvium 13 chemical elements). This map chart shows the distribution of the upper accumulative horizon of genesis different soils on the territory of biogeochemical potential. However, the agrogenic load being different in duration had also made its corrections in the pattern of biogeochemical heterogeneity. The difference between SQ2 and SQ1 is due to the involvement of additional elements such as Al, Ni, Pb and As, in its calculation, i.e. mainly pollutants, and the fact that the calculation of SQ1 takes into account the content of Ca, Sr, Mg, Cr and V. The largest area (69%) is occupied by a zone with SQ2 values from 0.32 to 0.46. These soils reflect the results of biological removal of organic carbon, macroelements and trace elements over the prehistory of agriculture. The main part of the territory of the field test site is characterized by a decrease in soil cover contrast due to the formation of

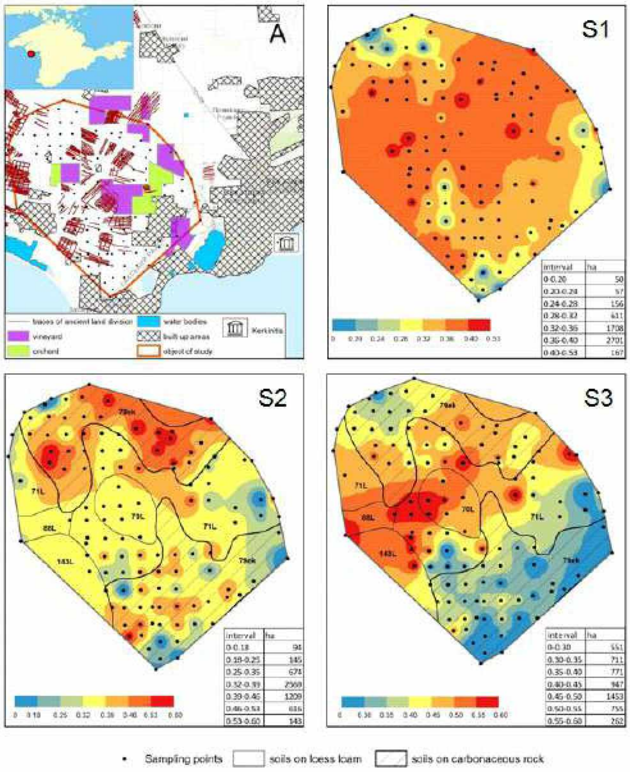

Fig. 1. The results of the geostatistical analysis of biogeochemical indicators at the research site: the location of the object of study (A); B-D-raster models of the distribution of soil properties: B-S1, C-S2, D-S3

geochemical homogeneity of the upper soil horizon under the influence of long-term agriculture. It is noteworthy that within the near-field *chora* there are focal zones with SQ2 values of >0.39 which are sometimes crossed by marking borders. The areas with the highest values of SQ2 (> 0.39) in the Northwest of the field test site clearly show a zone of new period agricultural development (last 150-165 years without prehistory). The location of this border can serve, as a confirmation of Kutajsov (2004) is opinion about wider territorial coverage by ancient agriculture than it was previously thought. In particular, for the territory of our field test site the area of lands with ancient history is 64%.

The duration of biological removal of 17 chemical elements (for loess soil) and 10 chemical elements (for soils on carbonate eluvium) characterizes the value of SQ3 (**Fig.** 1, D) which is represented in the predominant areas with values 0.45-0.50 (27%) and 0.50-0.55 (14%) and geographically close to the areas that form the value of SQ1=0.36-0.40 (49.6%) on (**Fig.** 1, B). These areas include clear traces of ancient land management. It is noteworthy that the lands being close to the city of Kerkinitis (soils on carbonate eluvium) can be regarded in terms of SQ3<0.40 as the least geochemically degraded ones (concentration of 9 chemical elements and Corg is closest for them with virgin conditions), although they are poorer in quality than the soil in the centre and in the northwest of the area under study. Thus, the position of the is oline with SQ3<0.40 values shows that the suburban lands, which were extensively used at least in 4-2 c. BC. occupied 37 per cent of the total area within the boundaries of the field test site.

CONCLUSION

The history of land use in the rural district of Kerkinitis suggested that those lands which had been initially (more than two centuries) influenced by the fallow farming system and subsequently (at 4-2 c. BC) became permanently used within the ownership of land would be most degraded. The intensity of agricultural impacts on the soil increased in the system of strictly ordered ancient land management due to increased requirements for commercial nature of crop production. However, the maximum values of soil quality, which are calculated according to the content of 16 most important nutrients for plants, are noted in the area of ancient regulated land use. This shows the role of agriculture in biogeochemical progradation of old arable soils due to more intensive soil weathering. At the same time, the initial soil-genetic differences in the territory are levelled, which allows us to conclude that the contrast of soil cover is reduced under the influence of long-term farming. This was especially clear when assessing the anthropogenic effects on soil quality of the selective accumulation of chemical elements in the soil in relation to parent rock, including a number of pollutant elements. The use of different ensemble chemical elements with the same geostatistical analysis procedures for the spatial variability allowed to establish the boundaries of the area of the current stage of agriculture (150–165 years) and the area of lands with ancient prehistory (64% of the research area). The proposed methodological approach to identify agricultural areas with different duration and biogeochemical transformation of soils uses objective procedures of geo-analysis and has heuristic capabilities, which makes it possible to recommend it for geoarchaeological studies for other areas of the ancient world and for analysis of soil-ecological monitoring results in areas with complex soil cover and with land use history.

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