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SOIL PHYSICS

Comparison of Areal and Profile Distribution of Magnetic Susceptibility in Steppe Soils of the Russian Plain

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Abstract—A comparative analysis of areal and profile measurements of magnetic susceptibility was carried out on the plots pf 100 m^2 in order to improve methods of surface soil sounding for mapping purposes and for identification of anomalies associated with anthropogenic pollution or disturbance of the surface soil layer. Two sites with Haplic Chernozems and one site with Haplic Kastanozem (Endosalic, Cambic) were studied. Additionally, a catena on the Yergeni Upland with different landscape positions (eluvial, transeluvial, transeluvial–accumulative) was studied. A comparison of the areal and profile magnetic susceptibility measured to a depth of 30 cm showed a direct correlation ($R^2 = 0.7$). The areal survey was found to correctly determine the volumetric magnetic susceptibility ($\varkappa_s$) to a depth of 30 cm. The $\varkappa_s$ variation at sites with different types of soils reflects soil–climatic zonality and spatial lithological heterogeneity expressed in different textures and mineralogical compositions of the upper (0–30 cm) soil layer within the test area of 10 × 10 m. The areal magnetic susceptibility of soils can be an important additional indicator capable of reflecting the features of soil-forming, lithological, and geochemical processes occurring in the upper soil layer. The $\varkappa_s$ variation at sites in different landscape positions is due to the development of sheet erosion and changes in the direction of iron oxidogenesis depending on the position of the soil profile in the relief. The set of areal and profile magnetic susceptibility measurements can be used to study soil inhomogeneities caused by anthropogenic, paleocryogenic, geomorphological, and lithogenic factors. In particular, this approach can be applied to the study of polluted soils and monitoring of agricultural lands.

Keywords: Chernozems, Kastanozems, iron compounds, soil magnetism, spatial heterogeneity

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INTRODUCTION

In recent years, remote sensing techniques have been widely introduced into soil research, which can potentially simplify regional soil mapping. However, they are ineffective where soils are under a camouflage cover of vegetation or other objects. Remote sensing techniques have difficulties due to errors of spectral ambiguity (e.g., different materials emitting similar spectra) and due to atmospheric scattering. In the early 1990s, a new direction—proximal soil sensing—was developed. It is based on continuous measurements of spatial changes in soil indicators in real time using near-surface geophysical methods (radar surveys, measurements of electrical resistance or conductivity, magnetic susceptibility, X-ray fluorescence, electromagnetic induction, etc.) to analyze the patterns of geospatial distribution of soils, but usually on small areas (≤1 ha) [24]. The usefulness of proximal sensing methods for agricultural, geotechnical, and archaeological research is well known [23, 30, 32, 34]. Despite this, further evaluation of such methods for regional soil mapping, including mapping of urban areas, is needed. One of these methods can be the measurement of magnetic susceptibility, since it is widely used for mapping urban soil pollution [10, 27–29]. Equipment for magnetic measurement methods is relatively cheap compared to other geophysical methods, is reliable and portable in the field, with simple data collection and little processing required to accurate identification of anomalous areas based on significant background measurements. Such equipment is universal for successful detection of various buried objects of forensic examination, disturbed soil, and surface-burnt areas in various types of soils and sediments [32].

Magnetic susceptibility is a standard physical parameter used to characterize soil-forming processes. It is widely applied in genetic soil science [7, 8, 32, 33], ecology [10], and paleopedology [2, 11, 19]. The demand for the magnetic susceptibility measurements is due to the simplicity of determination and the proven relationship with the physical, chemical, and mineralogical characteristics of soils [21, 36].

When studying the soil magnetic susceptibility, two types of measurements are routinely made. The first type is area measurements. They are carried out in the field on the soil surface, often using special sensors, such as the Bartington MS2D loop [22] or KT-5 kappameters [14]. The areal magnetic susceptibility values are used to build maps. With their help, erosion processes are modeled [25], mapping units are determined [37], soil cartograms are compiled [9], etc. The advantage of this measurement type is determined by its nondestructiveness, which makes it possible to obtain a picture corresponding to the natural one.

The second type is a profile measurement of magnetic susceptibility in soil horizons, including the parent material. It is carried out both in the field and in the laboratory. The characteristic of the profile distribution of magnetic susceptibility is an additional feature used to determine the soil type [13, 21], as well as to diagnose some elementary soil processes, such as gleying, illuviation, and alkalization [7]. The most efficient interpretation of magnetometric data in soil science requires the integration of the two considered types of measurements.

The magnetic susceptibility values in steppe soils are determined primarily by the contents of strongly and weakly magnetic iron compounds in the soil. The former are represented by ferromagnetic minerals, namely magnetite and maghemite. The formation of magnetite is associated with the dissimilatory activity of iron-reducing bacteria [2]. The newly formed fine magnetite can spontaneously oxidize to maghemite. The second group is represented by antiferromagnetic minerals, namely hematite and goethite. The formation of these minerals is believed to occur under competitive conditions. Goethite is formed from any source of iron through the solution [35]. Hematite is formed by the transformation (including dehydration) of ferrihydrite, even in the presence of excessive water [18]. The amount of these minerals in the soil, their size and dispersion determine the magnitude of the magnetic susceptibility.

Studies of soil magnetism over the past 20 years [2, 7, 12, 20, 27, 37] have shown that the magnetic characteristics logically change in the soil profile, but are heterogeneous in areal terms. Variation over the area is determined by the heterogeneity of the soil cover and different intensities of elementary soil processes [20]. These patterns cause an increased interest in the use of profile and area studies of the magnetic susceptibility for studying the spatial heterogeneity of soils.

Our study was aimed at a comparative analysis of areal and profile measurements of magnetic susceptibility to reveal variation in the iron oxidogenesis and to identify heterogeneities in the surface layer of steppe soils.

OBJECTS AND METHODS

Field studies were carried out in Rostov oblast (site 1), Stavropol region (site 2), and the Republic of Kalmykia (site 3). Site 1 was on arable land in the vicinity of Chumbur-Kosa (46°57′49″ N, 38°56′53″ E), on a gentle watershed slope. Ordinary chernozems (Haplic Chernozems according to the WRB system) were studied. Site 2 was in the vicinity of the Otkaznoe village (44°17′23″ N, 43°51′22″ E) in the upper part of a balka (flat-bottomed ravine) in the virgin area. Southern chernozems (Haplic Chernozems according to the WRB system) were studied at this site. Site 3 was in the vicinity of the Zunda-Tolga settlement (45°36′39″ N, 44°19′39″ E), on an interflueve. Light chestnut solonetzic soils (Haplic Kastanozems (Endosalic, Cambic) according to the WRB system) were studied at this site. Parent rocks for all the studied soils were loesslike loams.

In order to assess the influence of relief on the magnetic susceptibility, a catena was additionally studied on the Yergeni Upland; it included three sites at the eluvial (summit), transeluvial (upper slope), and transeluvial–accumulative (footslope) positions. The sites were laid near the Remontnoe village of Rostov oblast (46°32′59″ N, 43°41′33″ E). Light chestnut solonetzic soils (Haplic Kastanozems (Endosalic, Cambic) according to the WRB system) on loesslike loams were studied within the catena [14].

Field measurements of the volume magnetic susceptibility ($\varkappa_s$) on the sites were performed with a KT-20 device with a 3F-32 sensor (Terraplus, Canada) at a frequency of 1 kHz. The KT-20 is a portable field device designed to measure the magnetic susceptibility and conductivity of a sample. With the advent of 3F-32 sensor of the large diameter, it became possible to use the KT-20 system for shallow surveys to a depth of about 30 cm.

The 3F-32 sensor is 32 cm in diameter and features three operating frequencies that have been selected to provide specific advantages in magnetic susceptibility and conductivity measurements. The device allows one to perform single measurements in a specific location or to continuously collect data for mapping the entire area. The built-in GPS receiver supplies the data with location coordinates. In addition, the device has a built-in digital camera for visual documentation of samples of interest. This device makes it possible to obtain dimensionless $\varkappa_s$ values, which are expressed in 10^{-3} SI units. The measurements were carried out with a step of 1 m on a premarked area 10 × 10 m in size. After measurements within the area, an average soil sample was taken from three boreholes drilled to the depth of parent material through each 10 cm. Also, an average soil sample was taken from the layer of 0–30 cm at the corners of the plots. In the obtained samples, the specific magnetic susceptibility χ (10^{-8} m^3/kg) was measured under laboratory conditions with Kappabridge KLY-2 device and in parallel with a KT-20 device with a standard sensor with two operating frequencies of 1 and 10 kHz (similar to the common device KT-5). The correlation between $\varkappa_s$ and χ was determined by regression analysis with a significance coefficient $p < 0.05$.

The variography method was used to determine the spatial variability of the volumetric magnetic susceptibility. Variograms or experimental graphs of the semi-

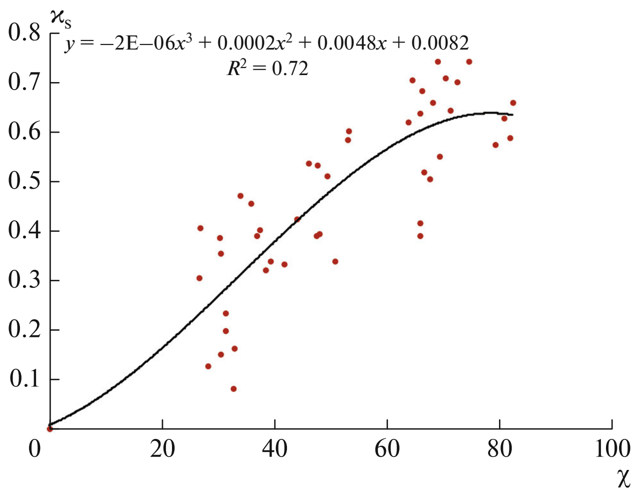

Fig. 1. Comparison of the magnetic susceptibility (χ) of soils in the upper 30 cm with the areal magnetic susceptibility ($\varkappa_s$).

variance dependence on the distance between testing points were built. The choice of the most suitable model was carried out using quality indicators. The semivariance was calculated by the formula:

$$\gamma(h) = 1/(2N(h))\sum[z(x_i) - z(x_i + h)]^2,$$

where $z(x_i)$and $z(x_i + h)$ are the results of $\varkappa_s$ measurements at points x_i and $x_i + h$, and $2N(h)$ is the number of pairs of points separated from one another by distance h [14, 29].

The resulting models were used to build cartograms with the kriging method. Its principle is based on determining the weight of the values of the variable at the surrounding points to estimate the value of the variable at the desired point or area. Variography and mapping of soil magnetic susceptibility were performed using the ArcMap 10.8 program.

RESULTS AND DISCUSSION

The results of areal measurements of the magnetic susceptibility $\varkappa_s$ with the KT-20 device with the 3F-32 sensor and profile measurements of χ down to a depth of 30 cm with the Kappabridge KLY-2 device showed a correlation. The found correlation indicates that the areal type of survey with the KT-20 device can correctly fix the magnetic susceptibility to a depth of 30 cm (Fig. 1). The $\varkappa_s$ or χ values were equal to 0 when measuring air, without contact with the sample.

Statistical analysis of the data showed that the mean and median values of the areal magnetic susceptibility ($\varkappa_s$) of soils at the studied sites do not differ significantly (Table 1). In terms of variation parameters (variation, coefficient of variation, standard deviation), the southern chernozem is characterized by the highest variability of values, and the light chestnut soil is characterized by the lowest variability of magnetic susceptibility.

The geostatistical method was used to study the $\varkappa_s$ spatial distribution. This method was previously used to study the spatial variability of individual soil properties in the dry steppe and steppe zones [16]. For the areal magnetic susceptibility measured at the studied sites, variograms were constructed (Fig. 2). The resulting variograms were approximated by Gaussian, exponential, and spherical models. Next, the model with the smallest mean standard error was chosen [31].

In all soils on the studied sites, there is spatial variation at different distances. For ordinary chernozem, this distance is 1–2.5 m. Of all the studied soils, only for ordinary chernozem, the variogram of the areal

Table 1. Statistical characteristics of the areal magnetic susceptibility

Parameter	Soil		
	light chestnut	southern chernozem	ordinary chernozem
Sample size	121	121	121
Lower quartile	0.58	0.48	0.54
Median	0.63	0.57	0.63
Upper quartile	0.72	0.65	0.70
Minimum	0.45	0.21	0.24
Maximum	0.94	1.06	0.85
Mean	0.65	0.57	0.62
Variation	0.01	0.02	0.01
The coefficient of variation, %	15.76	32.26	21.83
Standard deviation	0.09	0.18	0.11
Interquartile range	0.14	0.17	0.16
Standard error	0.0009	0.0015	0.0011

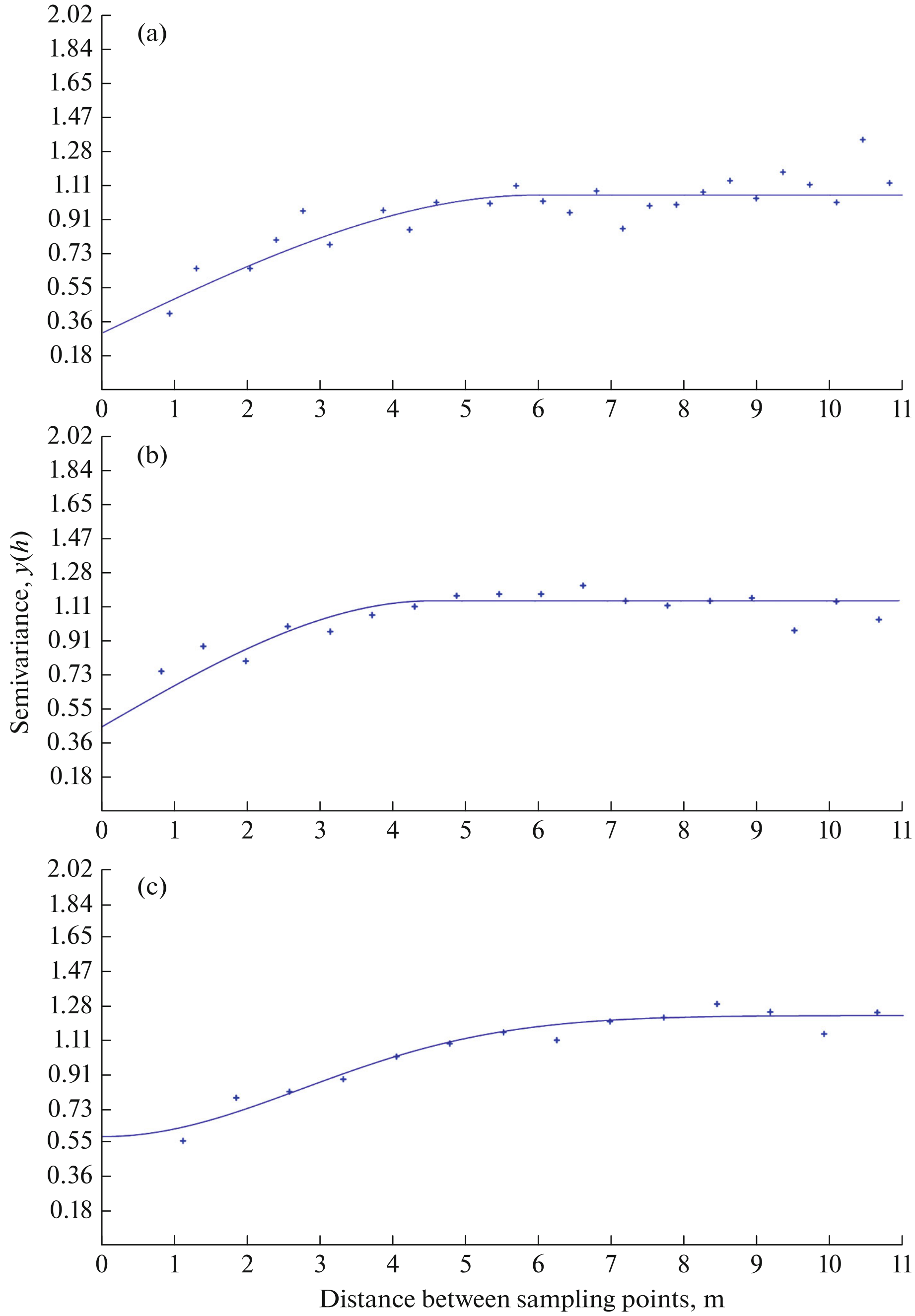

Fig. 2. Variograms of $\varkappa_s$ distribution in (a) ordinary chernozem, (b) southern chernozem, and (c) light chestnut soil. Dots are experimental averaged values; solid line is the result of approximation by the model.

magnetic susceptibility had a quasiperiodic form. Such a shape and a small distance of $\varkappa_s$ variation, apparently, can characterize tillage and microrelief changes. In this case, the admixture of a weakly magnetic material to the surface can occur, which should reduce the magnetic susceptibility values. This variation is cyclical and is manifested at short distance; as a result, the susceptibility values of the arable horizon consistently increase and decrease [9].

The variograms constructed for the volumetric magnetic susceptibility measured on sites with the southern chernozem and light chestnut soil have similar shapes. For the southern chernozem, the $\varkappa_s$ values vary at distances of 1–4 m, which is close to the ordinary chernozem. The shape of the variogram has some periodicity. For the light chestnut soil, variation occurs at distances of 1–6 m. The shape of the variogram has a weakly pronounced periodicity.

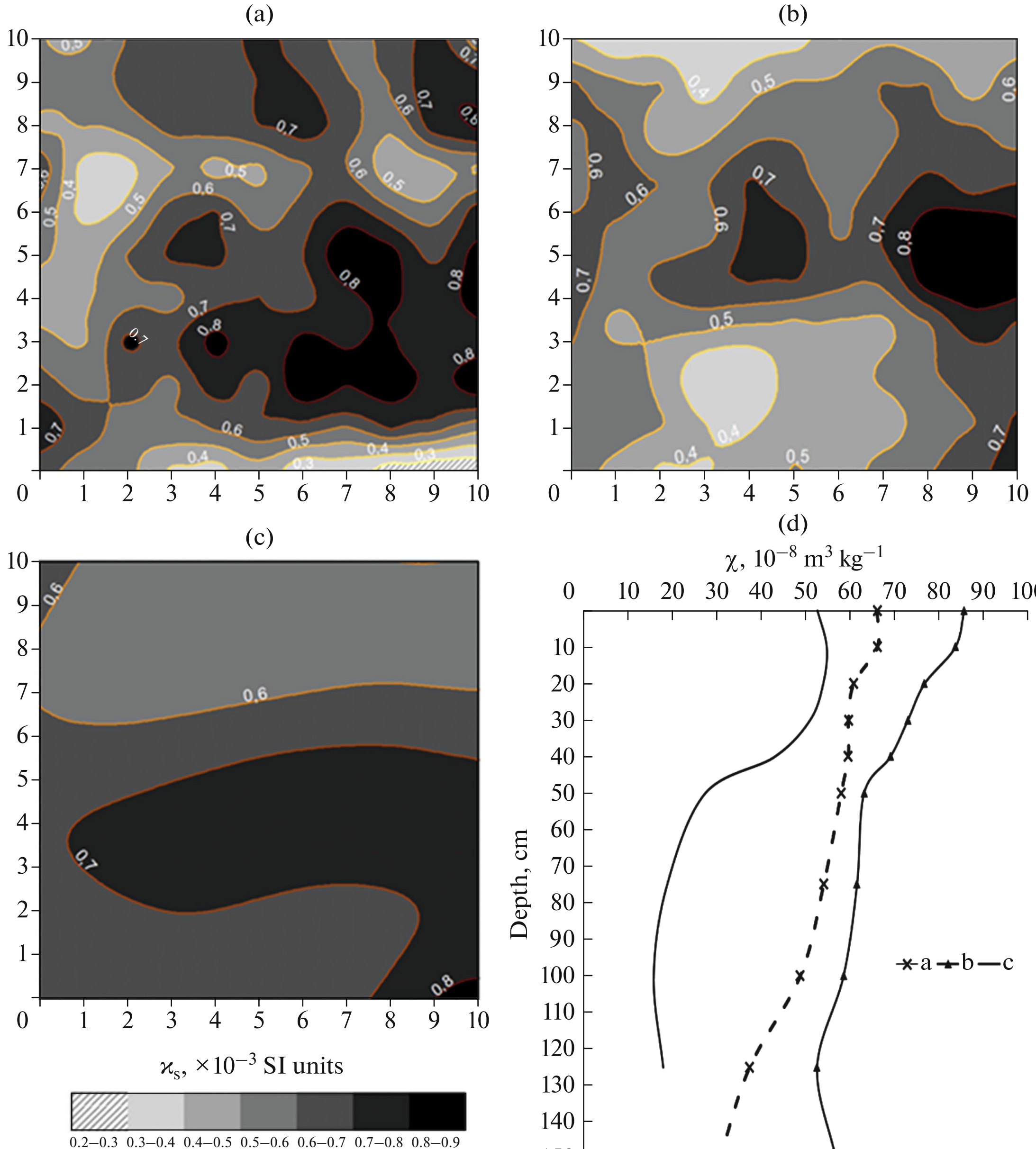

Fig. 3. Spatial maps of $\varkappa_s$ at sites of 10 × 10 m and profile distribution of χ in (a) ordinary chernozem, (b) southern chernozem, and (c) light chestnut soil.

Since the measurements were carried out in areas similar in size and in the same direction, hidden patterns found with variography in spatially distributed data can be associated with the presence of heterogeneous structures, which are manifested in the upper 0–30 cm soil layer. For a more detailed study of the $\varkappa_s$ spatial distribution, the variograms approximated by the models were used to construct kriging cartograms. The constructed cartograms clearly show the features of spatial variability in the layer of 0–30 cm of the studied soils (Fig. 3).

To characterize the spatial variation of the magnetic susceptibility, areal measurements were carried out in combination with profile measurements. The profile distributions of the specific magnetic susceptibility (χ) of steppe soils have accumulative patterns with a regular decrease in χ down the profile, where the highest values are confined to the upper horizons of the southern chernozem (85×10^{-8} m^3/kg), and the lowest values, to the parent rock (18×10^{-8} m^3/kg). This χ distribution is typical for the steppe soils of the Russian Plain [2].

In all the studied soils, the magnetic susceptibility in the upper soil horizons was higher than in the parent rocks. As shown earlier [3], during soil formation, highly magnetic minerals are formed in the upper horizons, predominantly in the clay fraction.

The variation of the volume magnetic susceptibility at the studied sites with the studied soils differs significantly. The $\varkappa_s$ spatial distribution maps for ordinary chernozem clearly demonstrate the variation as a result of plowing. The $\varkappa_s$ value within the studied area varies from 0.3 to 0.8×10^{-3} SI units. There are areas of 1–2 m in size with values of $0.4–0.5 \times 10^{-3}$ SI units. The $\varkappa_s$ values in the range $0.6–0.7 \times 10^{-3}$ SI units occupy 32% of the total area, and in the ranges of 0.5–0.6 and $0.7–0.8 \times 10^{-3}$ SI units, about 20% each. The specific magnetic susceptibility within the layer from 0 to 30 cm decreases from 66 to 60×10^{-8} m^3/kg. The data obtained indicate that, in addition to mixing of the material during plowing, there is a change in the hydrological, redox, acid–base, and biochemical conditions of the environment. As a result, the direction of the processes of formation, accumulation, and transformation of iron oxides in the soil changes [2, 35]. At the studied site with ordinary chernozem, variations of $\varkappa_s$ are determined by agricultural impact, which changes the direction and the rate of iron oxidization.

The profile distribution of magnetic susceptibility showed that the upper layers of the southern chernozem are characterized by the highest values of χ (from 85 to 76×10^{-8} m^3/kg), which decrease towards the parent rock. At the study site, the $\varkappa_s$ values have the greatest variation and are in the ranges of 0.3–0.4, 0.6–0.7, 0.7–0.8, $0.8–0.9 \times 10^{-3}$ SI units. These ranges are observed on 14% of the total area each. The $\varkappa_s$ values in the ranges of 0.4–0.5 and 0.5–0.6 occupy 18 and 23%, respectively. The study site was located on a virgin area with a vegetation cover of about 90% with a predominance of meadow forbs and grasses. Such spatial distribution of magnetic susceptibility in this area most likely depends on the microrelief, which determines the biogeochemical features and the species structure of vegetation, which can lead to different iron contents in the upper soil horizons [26].

At the site with the light chestnut soil, $\varkappa_s$ values in the ranges of 0.5–0.6, 0.6–0.7, $0.7–0.8 \times 10^{-3}$ SI units occupy 39, 29, 20% of the total surveyed area, respectively. The specific magnetic susceptibility distribution in the profile of the light chestnut soil also has an accumulative pattern with an increase in χ in the layer of 10–20 cm up to 54×10^{-8} m^3/kg, which can be conditioned by eluvial–illuvial redistribution of the clay fraction in the course of solonetzic process [5]. The weak variation of $\varkappa_s$ at the site with the light chestnut soil can indicate a relationship between the mineralogy of iron oxides and the conditions of soil formation, primarily with climatic conditions that determine the intensity of iron oxidogenesis, as well as with the degree of solonetz formation.

Thus, changes in the volumetric magnetic susceptibility over the area are primarily associated with the conditions of distribution, accumulation, amount and forms of iron minerals characteristic of the studied soil types. Areal magnetic susceptibility can reveal spatial soil heterogeneity, which is caused by the biogeochemical, geomorphological, and anthropogenic factors at the studied sites.

In a number of studies, magnetic susceptibility was used as a parameter reflecting the features of iron oxidogenesis, lateral migration of matter, and geochemical processes within the landscape catena [2, 14, 22]. In order to supplement the obtained results, a study was carried out to investigate the distribution of volumetric magnetic susceptibility at three sites located on the eluvial, transeluvial, and transeluvial–accumulative positions of the slope.

Changes in $\varkappa_s$ at the sites and χ in the soil profiles for different types of landscape are shown in Fig. 4. The values of $\varkappa_s$ and χ of the upper layer of light chestnut soils decrease from the eluvial to the transeluvial–accumulative position of the slope. Maximum $\varkappa_s$ values are typical for site A7-1 located in the upper part of the slope; it is characterized by the maximum coefficient of variation and the predominance of values in the range of $0.7–0.8 \times 10^{-3}$ SI units (43% of the total area). At sites A7-2 and A7-3, $\varkappa_s$ values on the same range are observed on 17 and 2% of the total area, respectively. The χ values in the layer of 0–30 cm from 39 to 31×10^{-8} m^3/kg from the eluvial to the transeluvial-accumulative position of the slope.

High values of $\varkappa_s$ and χ in soils within the eluvial position on the slope indicate that there is no lateral removal of matter in this type of landscape; accordingly, strongly magnetic iron minerals are accumulated in the upper part of the profile. This site is characterized by a strong $\varkappa_s$ variation, which can be due to the diversity and heterogeneity of the soil cover controlled by the microrelief [17]. Within 100 m^2, a combination of light chestnut, solonetzic, and meadow chestnut soils was observed. On the transeluvial and transeluvial–accumulative positions, the influence of sheet erosion becomes significant and the lateral migration of matter takes place. In the transeluvial position, the removal of silt and clay fractions from the upper soil layers begins, which leads to a decrease in magnetic susceptibility values. At the same time, coarse silt particles are accumulated in the transeluvial–accumulative zone, which determines the weak variation and low values of the magnetic susceptibility. Thus, magnetic susceptibility clearly fixes the heterogeneity of the texture of steppe soils. An important factor influencing the decrease in magnetic susceptibility from the eluvial to the transeluvial–accumulative position on the slope is an increase in pH towards alkaline conditions, an increase in the carbonate content, a decrease in the redox potential, and a change in the organic matter content, which leads to a weakening of the iron oxidogenesis depending on the position of the soil profile in the catena. As previously shown

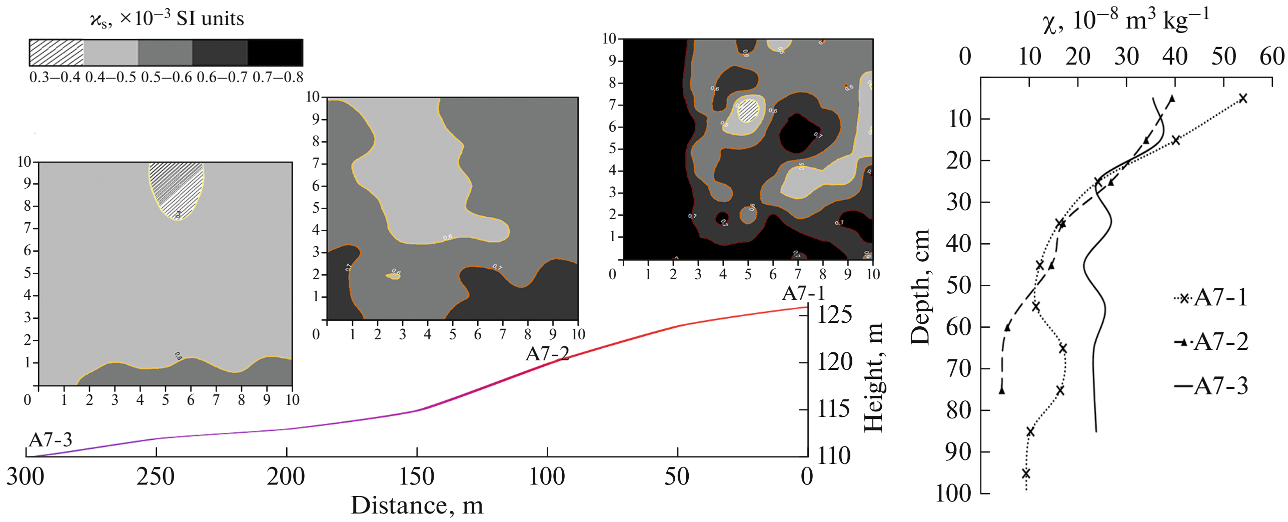

Fig. 4. Spatial maps of $\varkappa_s$ at sites of 10 × 10 m and profile distribution of χ for soils of different positions in the catena: eluvial (A7-1), transeluvial (A7-2), and transeluvial–accumulative (A7-3).

[1, 4, 5], depending on the position of the soil in the conjugated geochemical landscape, different transformation conditions for mineral matter during soil formation are created and affect the state of iron compounds. The soils of eluvial landscapes are characterized by an increased oxidation degree compared to the soils of subordinate landscapes, even at a higher degree of biogenicity and higher moisture content. This is due to a significant supply of oxygen with atmospheric precipitation and a greater degree of drainage of the eluvial landscape. Floodplain soils occupy a special area in the Eh–pH coordinates. Compared to automorphic soils, they are characterized by a greater variety of redox conditions, but a much smaller pH range [1, 4, 6, 14, 15].

The obtained data demonstrate that the use of a set of profile and area measurements of magnetic susceptibility is a sensitive tool that allows determining the heterogeneity of the soil cover caused by natural and anthropogenic factors.

The widespread use of magnetic susceptibility to study soils contaminated with heavy metals, soils of archaeological monuments, or to assess the impact of climate change on soils [2, 10, 11, 27, 28] and the obtained results suggest that area studies can significantly expand information on the magnetic soil properties. Taking into account the simultaneously measured soil parameters with a KT-20 device, it is possible to carry out multiple studies of the soil cover and obtain additional information on the water and salt regimes based on the on the soil specific electrical conductivity data. These measurements have been performed at all the studied sites, but their results are not discussed in this article.

CONCLUSIONS

The maps of spatial distribution of volume magnetic susceptibility $\varkappa_s$ give visual representation of the heterogeneity of steppe soil properties in the upper (0–30 cm) layer. In this regard, we recommend relying on maps of the areal distribution of magnetic susceptibility when planning sampling points for magnetometric studies of soil profiles.

Areal magnetic susceptibility can reveal spatial soil heterogeneity, which is caused by geomorphological, biogeochemical, and anthropogenic factors. Variation in $\varkappa_s$ values at the test sites with different soils (ordinary chernozem, southern chernozem, light chestnut soil) is mainly associated with the heterogeneity of distribution, accumulation, amount, and forms of iron minerals. Changes in $\varkappa_s$ at sites in different positions on the slope occur under the influence of sheet erosion and weakening of iron oxidogenesis depending on the position of the soil profile in the catena.

A set of areal and profile measurements of magnetic susceptibility can be used to study soil heterogeneities caused by anthropogenic and natural factors.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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