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Characterization of the spatial heterogeneity of the agrochemical properties of arable chernozem soils in areas with a heterogeneous relief in the aspect of variable rate application

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Abstract. The heterogeneous relief leads to an uneven distribution of nutrients in the redistribution of crop rotation fields, which creates the prerequisites for contamination of adjacent environments and introduces risks to the production of eco-products when applying mineral fertilizers calculated for the entire. Taking into account the uncertainty introduced by the relief into the spatial distribution of soil fertility indices increases the accuracy of the VRA maps. However, it is often moved beyond the interests of introducing precision farming technologies. In this work, using various methods of regression modeling, the characteristic of the variability of the properties of chernozem soils on two arable lands with different heterogeneous relief is given. In the area with heights from 80 to 140 m, the relief determines from 24 to 58% of the spatial variability of soil properties, and in the area with a flat relief (110-150 m), the proportion of the dispersion of soil parameters described by the relief is much lower and amounts to 13-30%. It is shown that, in areas with significant elevation differences, it is possible to use regression techniques to describe the spatial distribution of soil properties, while in leveled areas, regression models need to be supplemented with a geostatistical description of spatial heterogeneity.

1. Introduction

Precision farming is currently considered not only as a modern methodology for ensuring the rational use of mineral fertilizers and ensuring an increase in crop yields, but also in environmental aspects [1, 2]. The introduction of variable rate application (VRA) ensures a decrease in the anthropogenic load on the environment adjacent to arable lands, as well as the receipt of eco-products by optimizing the doses of applied mineral fertilizers. In accordance with this, it becomes extremely important to describe the spatial heterogeneity of arable land in terms of the availability of nutrients, and to study the patterns of its formation. The heterogeneity of the nutrients content in arable land is largely influenced by their redistribution over relief elements. The influence of the relief on the spatial heterogeneity of the soil cover can be manifested both directly during the formation of soil properties as a result of their formation, and indirectly through the influence on the development of erosion processes occurring on arable land [3]. The heterogeneity of the relief should be taken into account when describing the stated variability of soil properties, including mapping for VRA. At the same time, it should be understood that the relief introduces a different amount of uncertainty in the



distribution of soil fertility indicators, which determines the choice of technique for describing their variability. Currently, there are many techniques for obtaining maps of the spatial distribution of soil properties for precision farming, which primarily relate to geostatistical methods (various types of kriging) [4]. However, the classical methods of geostatistics do not take into account the factors affecting the distribution of soil properties over the field.

2. Materials and methods

As objects for research, we used two fields of grain-row crop rotations of the chernozem zone of the Republic of Tatarstan. The fields are heterogeneous in terms of relief conditions. The field (No. 1) ($S = 254$ ha) is located in Zainsky district of the Republic of Tatarstan. The site is characterized by a significant elevation difference (up to 60 m) with steep slopes in the southwestern part of the field. The soil cover is represented by non-eroded, slightly eroded and medium-eroded leached chernozems, which are quite different in fertility. The second field (No. 2) ($S = 287$ ha) is located in Sarmanovsky district of the Republic of Tatarstan on a gentle slope of the northeastern aspect, the elevation difference is less than 30 m. The soil cover is also represented by leached chernozems. Erosion of soils in the field is weak, therefore, along with uneroded leached chernozems, only slightly eroded chernozems are found.

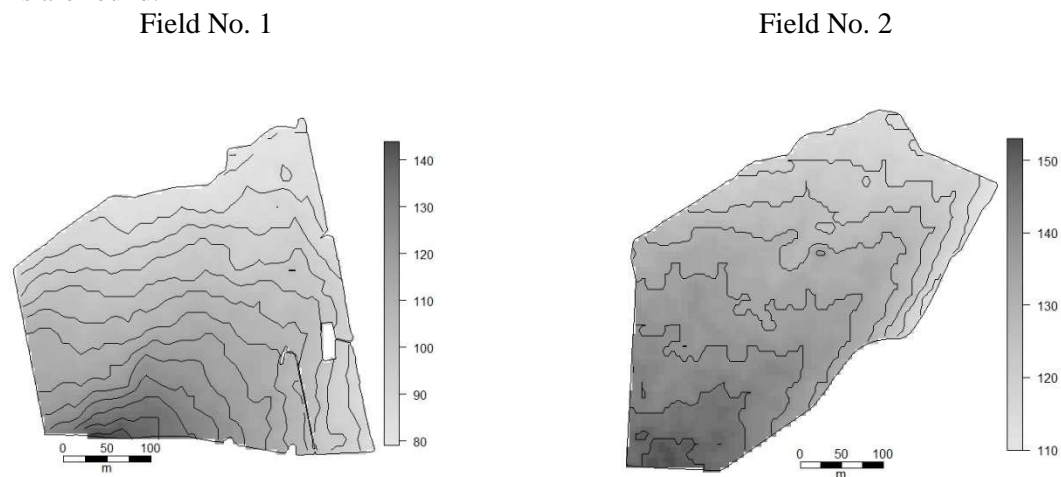


Figure 1. Digital elevation model maps of two plots.

The fields were divided into elementary rectangular plots with an area of 5 hectares. In accordance with the current state standard [5], mixed samples were taken from each elementary site, which were made up of 20-40 single samples. The total number of samples in field No. 1 was 50 samples, in field No. 2 - 59 samples. Hydrolysable nitrogen by the Kornfield method and available forms of phosphorus and potassium by the Chirikov method were determined.

The influence of relief on the spatial distribution of soil properties was assessed using statistical modeling based on regression models (Fig. 1). The modeling stage consisted of building statistical models with the inclusion of explanatory variables, which are morphometric attributes of the relief of the study area. The following models were used in the work: multiple linear regression model (MLR), multiple linear regression model with generalized least squares estimation, both with the inclusion of the spatial structure parameter (GLS + corr) and without it (GLS).

The morphometric characteristics of the relief were obtained from an SRTM digital elevation model with a spatial resolution of 30 m (URL: <https://lta.cr.usgs.gov/SRTM1Arc>) and calculated using the SAGA GIS software [6]. In total, 22 morphometric attributes of the relief were used, which characterized both the change in the gradient of the terrain elevations and the measure of topographic heterogeneity. The digital elevation model was preliminary processed by smoothing filtering to

remove artifacts when calculating morphometric variables. Working with raster images and modeling was carried out in the environment of the object-oriented language R.

The morphometric attributes of the relief were brought to a unified scale by data normalization. Normalized values were calculated using the following formula:

$$X_p = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}}$$

where X_p – normalized value, x_i – original value, x_{\max} , x_{\min} – maximum and minimum value of the attribute, respectively.

The models were evaluated after the LOOCV cross-validation procedure. The criterion for choosing the best regression model was the Akaike information criterion (AIC) and ANOVA results.

$$AIC = -2 \log(L(\hat{\theta})) + 2K$$

where $L(\hat{\theta})$ represents the maximum likelihood / probability of the estimated parameters $\hat{\theta}$ according to the model. The parameter $\hat{\theta}$ mainly quantifies the effect of the explanatory variables on the model and includes the intersection point, regression coefficients, and residual variance. K is the number of free parameters in the model.

3. Results

Table 1 presents the statistical characteristics of the agrochemical properties of the surveyed fields.

Table 1. Descriptive statistics of agrochemical indicators

Field	Nutrient	N, mg·kg ⁻¹	P ₂ O ₅ , mg·kg ⁻¹	K ₂ O, mg·kg ⁻¹
No. 1	Mean	100.4	149.4	226.5
	Coefficient of variation, %	19.4	34.2	19.1
	Lower quartile	88.6	108.7	195.2
	Median	98.0	138.7	230.7
	Upper quartile	110.3	175.3	250.7
	Interquartile range	21.7	66.7	55.6
No. 2	Mean	140.0	131.3	163.3
	Coefficient of variation, %	16.3	42.3	25.1
	Lower quartile	128.2	88.7	130.1
	Median	136.1	112.8	152.8
	Upper quartile	149.6	167.9	190.1
	Interquartile range	21.4	79.3	60.0

The studied soils of the fields differ in the content of nutrients. The mean content of hydrolyzable nitrogen for field No. 1 is 100.4 mg·kg⁻¹, for field No. 2 – 140 mg·kg⁻¹. The mean content of mobile phosphorus for field No. 1 is 149.4 mg·kg⁻¹, for field No. 2 – 131.3 mg·kg⁻¹. The mean of mobile potassium for field No. 1 is 226.5 mg·kg⁻¹, for field No. 2 – 163.3 mg·kg⁻¹. The variability of the hydrolyzable nitrogen of the two fields is characterized as average ($V_{\text{field 1}} = 19.4\%$, $V_{\text{field 2}} = 16.3\%$). The variability of mobile phosphorus is defined as very strong ($V_{\text{field 1}} = 34.2\%$, $V_{\text{field 2}} = 42.3\%$). The variability of the content of mobile potassium on field No. 1 has an average variability ($V_{\text{field 1}} = 19.1\%$); the variability of field No. 2 is strong ($V_{\text{field 2}} = 25.1\%$).

As a result of the modeling, it was found that the best model for the content of hydrolyzable nitrogen (Field No. 1) was recognized as the multiple linear regression model with generalized least squares estimation (MLR GLS) (Tab. 2). The model of the same type was the best of those considered in the case of the content of mobile phosphorus in both fields. The inclusion of the spatial correlation structure slightly improved the considered regression models, which made it possible to select the models with the inclusion of the spatial structure parameter as the best among the considered ones.

Thus, these models more fully, in comparison with the multiple regression model and the generalized squares model, describe the spatial distribution of the mobile potassium content of the two fields, as well as the content of hydrolyzable nitrogen in field No. 2. In general, the use of generalized least squares regression allowed for heteroscedasticity in the models.

Table 2. Values of the Akaike information criterion for regression models

Model for field No. 1	AIC		Model for field No. 2
	Field No. 1	Field No. 2	
Hydrolysable nitrogen			
MLR	419.77	525.17	MLR
MLR GLS ^a	406.85	487.19	MLR GLS
MLR GLS+corr	407.85	483.93	MLR GLS+corr ^a
Mobile potassium			
MLR	473.19	602.21	MLR
MLR GLS	433.83	609.57	MLR GLS
MLR GLS+corr ^a	431.74	609.46	MLR GLS+corr ^a
Mobile phosphorus			
MLR	528.36	638.54	MLR
MLR GLS ^a	518.82	631.74	MLR GLS ^a
MLR GLS+corr	522.67	635.72	MLR GLS+corr

^a The final best models

From the entire set of morphometric attributes of the relief that could potentially affect the spatial distribution of agrochemical indicators, based on the results of the final modeling, several morphometric values were selected that significantly affect the studied of soil properties (Tab.3).

Table 3. Morphometric attributes of the relief as a predictors in the resulting models of the agrochemical soil properties spatial distribution

Target variable	Predictor	Determination coefficient R ²	Predictor		Determination coefficient R ²
			Field No. 2		
			Field No. 1	Field No. 2	
Hydrolysable nitrogen	Catchment Area	0.43	Topographic Position Index		0.30
	Elevation		Elevation		
Mobile potassium	Cross-Sectional Curvature	0.58	Convergence Index		0.16
	Slope Height		Flow Accumulation		
	Topographic Position Index		Topographic Position Index		
Mobile phosphorus	Valley Depth	0.24	Longitudinal Curvature		0.13
	Slope Height		Elevation		
	Elevation				

The agrochemical properties spatial distribution in field No. 1 is influenced by the elevation and cross-sectional curvature of the terrain, the catchment area, valley depth, slope height and topographic

position index. Field No. 1 is located on a steeper slope and is more eroded, which is reflected on the influence of the relief on the soil properties spatial distribution. For example, the coefficient of determination for the content of hydrolyzable nitrogen in the model with morphometric attributes of the relief is $R^2 = 0.43$, and for the content of mobile potassium it increases to $R^2 = 0.58$. The distribution of the phosphorus content in this area is explained by the attributes of the relief only by 24%, which may be due to the uneven accumulation of phosphorus and the fixation by clay minerals of the underlying horizons, which emerge locally on the day surface due to erosion activity.

The second field is flatter and the influence of the relief on the agrochemical properties distribution in this area is weak. The above is confirmed by the low values of the models of coefficients determination. Its greatest value is achieved in the case of hydrolyzable nitrogen and is $R^2 = 0.30$; the models for the content of mobile forms of potassium and phosphorus have values $R^2 = 0.16$ and $R^2 = 0.13$, respectively. The variance of the agrochemical properties values in field No. 2 is explained by such morphometric attributes as topographic index and elevation, longitudinal curvature, and convergence index.

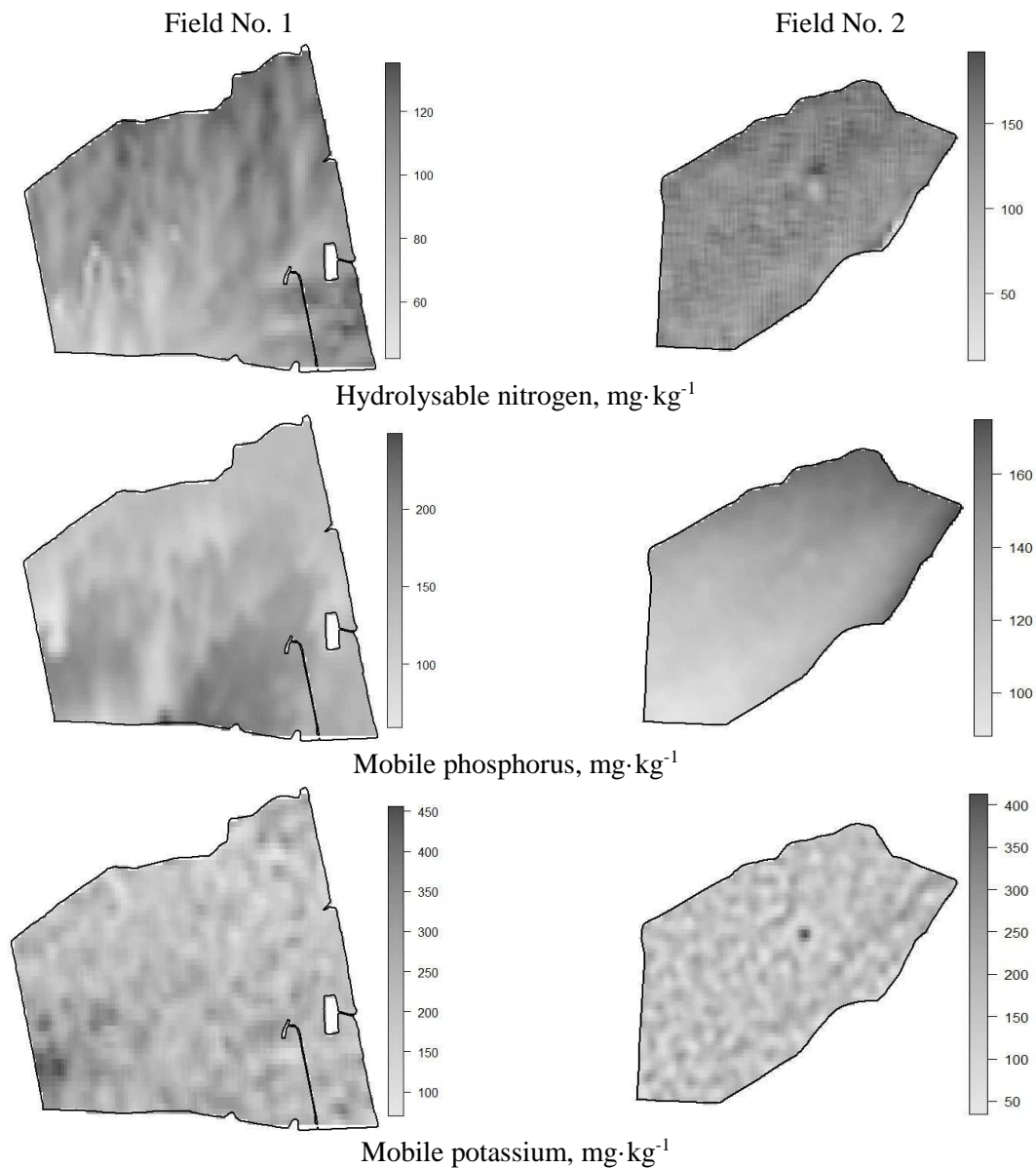


Figure 2. Maps of the spatial distribution of soil properties obtained as a result of regression modeling

Based on the modeling results, maps of the soil properties spatial distribution were built (Fig. 2). In field No. 2, the spatial variability of properties is described worse than those in field No. 1, which is due to the low indicators dependence on the relief characteristics. At the same time, the very strong variability of the mobile phosphorus and strong variability mobile potassium values spatial distribution depends not only on the relief, but there are other factors that can be used in regression models. The use only geostatistics classical methods, such as ordinary kriging, makes it possible to describe the spatial distribution of indicators with sufficiently large samples set, which increases the cost of compiling maps for VRA. At the same time, the use of only regression modeling to describe the soil properties variability is appropriate more or less in areas with the significant elevation difference. The combination of regression modeling with classical geostatistical techniques implemented in hybrid models (for example, regression kriging) allows us to describe the variability of indicators with high accuracy [7].

4. Conclusion

In the work, regression modeling was used to characterize the spatial heterogeneity of soil fertility indicators in areas with heterogeneous relief. It is shown that with a significant difference in elevation, regression models can describe from 24 to 58% of the spatial variability of soil properties, while in areas with a flat relief, the described dispersion proportion of soil parameters is much lower – 13-30%. To obtain VRA maps, the intra-field variability description of soil parameters should be supplemented with the techniques of geostatistical and hybrid modeling.

5. Acknowledgements

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