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USING ANALYTICAL HIERARCHY PROCESS TO DETERMINE INTRA-FIELD HETEROGENEITY ZONES UPON IMPLEMENTATION OF PRECISION FARMING

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Abstract
The study aimed to develop a methodology for determining zones of intra-field heterogeneity for precision farming. In this study, we took into account the Belarussian national land use system which provides for the absence of private ownership of agricultural land. The spatial distribution of intra-field heterogeneity zones within the land use area of 7549.49 thousand hectares was identified using the analytical hierarchy process (AHP). The algorithm for determining zones of spatial heterogeneity provides for: (1) the selection of indicators and their ranking; (2) developing a pairwise comparison matrix, (3) estimating relative weights and (4) assessing matrix consistency. It is recommended to use data from agrochemical soil studies which are conducted centrally every 4 years for each agricultural enterprise as input parameters. These data include the humus content in the soil, the content of available phosphorus and potassium, soil pH, and the content of B, Cu, Zn, Ca, and Mg. The data should be carefully examined using spatial statistics tools to provide a more accurate delineation of the management-zones boundaries. The developed technique makes it possible to determine fertile and marginal areas within each field and differentiate the use of fertilizers, taking into account the presence of intra-field heterogeneity. This will reduce the total cost of purchasing and applying phosphorus fertilizers by 34 $\$\cdot ha^{-1}$ and potash fertilizers by 9 $\$\cdot ha^{-1}$ due to the redistribution of the fertilizer dose calculated for the planned yield, taking into account the identified site-specific management zones. At the same time, the level of chemical pressure per hectare of arable land will decrease by 6.7% without loss of crops productivity.
Key words: land management, GIS, analysis of hierarchies, precision farming, profitability.

Introduction

Agriculture is the most important area of the world economy, which ensures global food security. The agricultural sector is responsible for the production of sufficient raw materials and food for the ever-increasing population. According to a UN report [World Population Prospects…, 2019], the world population is expected to increase by 2 billion people in the next 30 years, from 7.7 billion today to 9.7 billion in 2050 [Loures et al., 2020]. Simultaneously with population growth, due to increased erosion processes and desertification caused by global warming, there is a widespread reduction in areas suitable for growing crops.

In particular, the reduction in the area of arable land in Europe, according to forecast estimates, will reach 1.12% by 2030 [EU agricultural outlook…, 2018]. If approaches to agricultural production are not revised, the global amount of arable and productive land per person in 2050 will be reduced to 25% of the 1960 level [Arsenault, 2014], and land degradation by 2050 will threaten the existence of about 3.2 billion people [Scholes et al., 2018]. These facts, coupled with the constant rise in the cost of energy resources and raw materials for the production of mineral fertilizers, as well as the shortage of organic fertilizers, necessitate the search for more effective ways to manage profitability and reduce the cost of agricultural products. One of the ways to successfully solve this problem is the introduction of innovative technologies in land use, in particular, precision farming technology [Мыслыва et al., 2021]. The International Society of Precision Agriculture (ISPA) defines precision agriculture as: «management strategy that gathers, processes and analyses temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production» [Precision Ag Definition …, 2019; Myslyva et al., 2021]. An important condition for the effective implementation of precision farming is the identification of zones of intra-field heterogeneity or site-specific management zones, which are taken into account when performing various technological processes in crop production [Méndez-Vázqueza et al., 2019]. At the moment, a unified methodology for identifying management zones has not been developed yet, and researchers offer various approaches to their definitions for precision farming [Shannon et al., 2018; Yuxin et al., 2018; Edge, 2019]. Taking into account the peculiarities of land use and land tenure in Belarus, which are the absence of private ownership of agricultural land and the presence in the country of predominantly large agricultural enterprises with an average area of arable land over 3.5 thousand hectares [Agriculture of the Republic of Belarus…, 2021]. The most optimal methodological approach to identifying intra-field heterogeneity zones is the approach in which the division of the management zones is carried out with the values of several soil characteristics. As universal initial parameters, it is advisable to use indicators that are mandatory for determination during agrochemical surveys of agricultural land and are used by the agronomic services of agricultural enterprises when calculating the application rates of mineral fertilizers and chemical ameliorants [Myslyva et al., 2021]. These indicators primarily include the content of mobile phosphorus and potassium, the content of humus, and the pH of the soil solution. The list of soil parameters recommended for determining intra-field heterogeneity zones can be expanded, based both on the availability of geospatial data on certain soil properties and on the requirements for determining management zones. In particular, this may include data on the content of trace elements, as well as on the level of soil contamination with residues of pesticides, heavy metals, and radionuclides. However, regardless of the approach and parameters used, a universal tool for identifying intra-field heterogeneity zones is the use of the functionality of geographic information systems (GIS) and mathematical analysis methods, in particular, the Analytic Hierarchy Process (AHP). This method involves considering a problem or phenomenon as a multi-level hierarchical structure that takes into account the relationship between its elements [Yeh et al., 2008; Zghibi et al., 2020]. Each element of the hierarchy can represent various: material and non-material factors; measurable quantitative parameters and qualitative characteristics; objective data and subjective expert assessments [Saaty, 2008]. Based on the foregoing the study aimed to develop a methodology for identifying intra-field heterogeneity zones for precision farming, based on the joint application of geoinformation analysis and AHP. To achieve the goal of the study, the following tasks were solved: 1) processing of initial data on soil parameters and creation of thematic layers with corresponding attributive information; 2) search for plots with different land quality according to a complex of 9 parameters using the AHP; 3) assessment of pairwise comparison matrix consistency by determining the value of the consistency index CI and the consistency ratio CR.; 4) detecting and mapping intra-field spatial heterogeneity zones.

Methodology of research and materials

Study area

The studies were carried out in 2020–2022 in the Orsha district of Vitebsk region (Republic of Belarus) within the land use of RPUE "Ustie" NAS of the Republic of Belarus on an area of 7549.49 thousand hectares of arable land. The locational map of the study area is shown in Fig. 1.

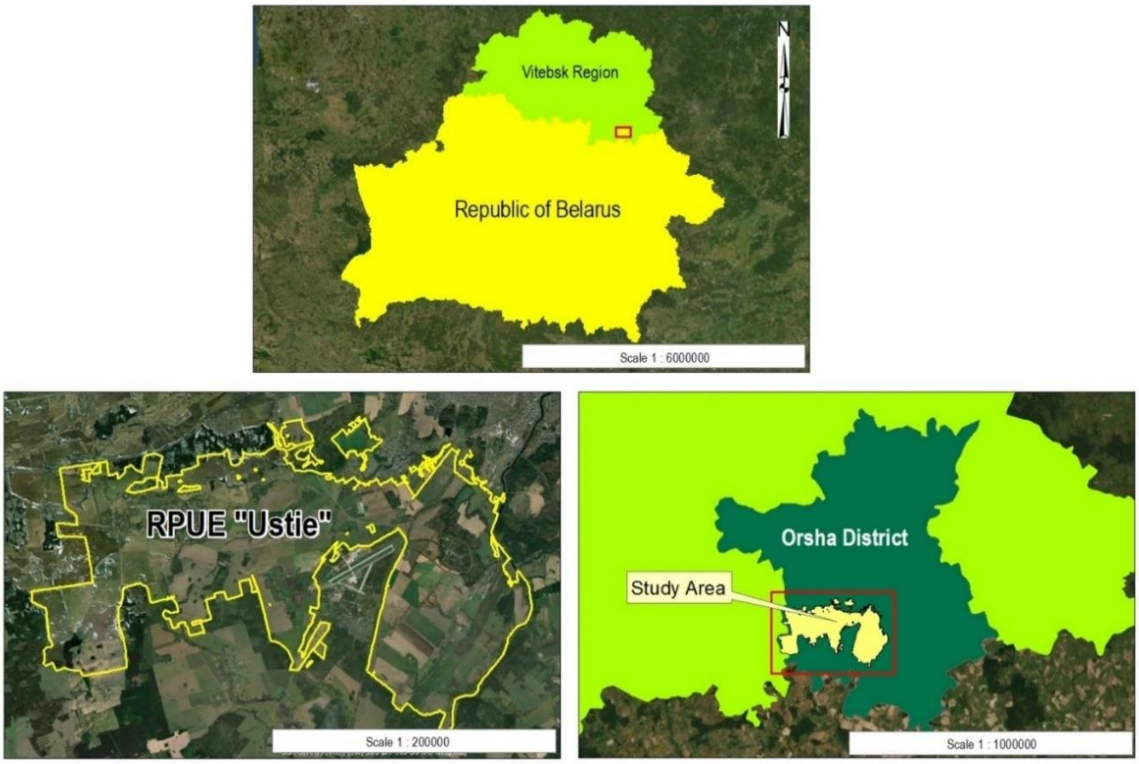

Fig. 1. Locational map of the study area

Data and materials

The shape file with the placement of lands within the study area was created based on the results of the digitization of planning and cartographic materials, which were obtained from the agrochemical survey of the territory of RPUE "Ustie" NAS of the Republic of Belarus, executed in 2019 by the Vitebsk regional design and exploration station of agrochemicalization. The soil cover of the study area is represented mainly by Luvisols and Retisols. To identify the intra-field heterogeneity zones, nine soil parameters were used. These parameters are standard for agrochemical surveys, which are mandatory for each agricultural enterprise and are carried out centrally every four years. The main statistical characteristics of the dataset used in the study are presented in Table 1.

Table 1

Statistical characteristics of soil parameters used to identify intra-field heterogeneity zones, n = 1292

Parameter	**Parameter value**			**Sd**	**C_v, %**	**Med**	**Skewness**	**Kurtosis**
	min	**max**	**mid**					
P_2O_5, mg·kg^{-1}	40	450	212	102	48.1	188	0.85	2.98
K_2O, mg·kg^{-1}	42	450	242	99	40.9	244	0.12	2.38
pH_{KCl}	4.53	7.41	6.08	0.48	7.9	6.15	-0.50	3.21
Humus, %	1.17	3.20	2.18	0.57	26.1	2.07	0.48	2.09
Cu, mg·kg^{-1}	0.70	5.10	2.29	0.83	36.2	2.10	1.64	5.75
Zn, mg·kg^{-1}	1.0	10.3	3.02	1.69	56.0	2.50	1.90	7.27
B, mg·kg^{-1}	0.29	1.10	0.77	0.20	26.0	0.75	0.07	1.92
Ca, mg·kg^{-1}	137	2810	1444	270	18.7	1397	0.45	3.83
Mg, mg·kg^{-1}	135	546	384	58.9	15.4	393	-0.68	2.96

Note: Sd is the standard deviation; C_v is the coefficient of variation; Med is the median.

Among these parameters, two indicators had a distribution close to normal (pH_{KC}l and calcium content), two indicators had a leptokurtic distribution (the content of acid-soluble copper and zinc), and the remaining indicators had a platykurtic distribution. The pH_{KCl} of the soil solution and the content of magnesium had a negative asymmetry, and their mean values were less than the median ones. For each of the parameters, a raster image of its spatial distribution within the area of interest was created. Raster images were created by ordinary kriging using ArcGIS 10.5. The presence of the intra-field spatial heterogeneity zones was determined by integrating nine thematic layers and their respective percentages through overlay analysis in the ArcGIS 10.5 environment [Chatterjee et al., 2020].

Analytic Hierarchy Process (AHP)

The spatial distribution of intra-field heterogeneity zones was identified using the analytical hierarchy process (AHP) [Saaty, 1980; Zghibi et al., 2020]. AHP allows to combination and converting geospatial data (input) into the resulting vector layer of zones with different land quality (output), by converting qualitative information from individual thematic layers into quantitative estimates on the Saaty scale [Saaty, 2008]. The method was implemented in four steps: (1) selecting soil parameters and their ranking (2) developing a pairwise comparison matrix, (3) estimating relative weights and (4) assessing matrix consistency. In the first step of the AHP, each soil parameter was given a score between 1 and 9, depending on its significance compared to the other parameters in pairwise comparisons [Zghibi et al., 2020]. For this, a standard Saaty's 1–9 scale was used (Table 2) to describe the relative influence of parameters.

Table 2

Analytic Hierarchy Process (AHP) relative class rate scale according to Saaty [Saaty, 2008]

Importance	**Equal**	**Weak**	**Moderate**	**Moderate Plus**	**Strong**	**Strong Plus**	**Very Strong**	**Very, Very Strong**	**Extreme**
Scale	1	2	3	4	5	6	7	8	9

1/9 1/8 1/7 1/6 1/5 1/4 1/3 1/2 1 2 3 4 5 6 7 8 9

← Less important | More important →

Then, a pairwise comparison matrix (PCM) [Abrams, 2018; Zghibi et al., 2020; Lentswe, Molwalefhe, 2020] was constructed (Equation (1)) using Saaty's scores obtained in the previous step. In the PCM, the matrix column is constructed based on a descending order of soil parameters. The first element is assigned a score of 1 when compared to itself (Table 3). Other elements of the rows are filled using the actual Saaty's scores when a more influential parameter is compared with a less influential parameter or the reciprocal of Saaty's scores when a less influential parameter is compared to a more influential parameter.

$$A = \begin{bmatrix} X_{11} & X_{12} \dots & X_{1n} \\ X_{21} & X_{22} & X_{2n} \\ \dots & \dots & \dots \\ X_{n1} & X_{n2} & X_{nn} \end{bmatrix} \quad (1),$$

Where A is a pairwise comparison matrix where element X_{nn} denotes the relative significance of one parameter compared to another relative.
Table 3 provides the PCM for the parameters used in this study. The phosphorus content was chosen as the first parameter of the matrix, as it has a greater influence compared to the other factors. Therefore, magnesium content was assigned a value of 9 as the least influential parameter. Potassium content was chosen as the second most important parameter, followed by soil acidity, humus, copper, zinc, boron, and calcium content in descending order. Each parameter in the selected set was assigned a Saaty score depending on its significance for determining zones of infield heterogeneity.

Table 3

Pair-wise comparison matrix of parameters affecting the spatial distribution of intra-field heterogeneity zones

Parameter and its designation	Ph	Po	Sa	Hu	Cu	Zn	B	Ca	Mg
Phosphorus (Ph)	1	2	3	4	5	6	7	8	9
Potassium (Po)	1/2	1	2	3	4	5	6	7	8
Soil acidity (Sa)	1/3	1/2	1	2	3	4	5	6	7
Humus (Hu)	1/4	1/3	1/2	1	2	3	4	5	6
Copper (Cu)	1/5	1/4	1/3	1/2	1	2	3	4	5
Zinc (Zn)	1/6	1/5	1/4	1/3	1/2	1	2	3	4
Boron (B)	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3
Calcium (Ca)	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2
Magnesium (Mg)	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1
Total	2.83	4.72	7.59	11.45	16.28	22.08	28.83	36.50	45.0

Further, the parameters were assigned weights derived by normalizing the pair comparison matrix (NPCM) [Rezaei-Moghaddam, Karami, 2007; Zghibi et al., 2020]. The NPCM elements were computed by dividing thematic element values by their corresponding total column values from the PCM (Table 4).

Table 4

Standardized pairwise comparison matrix and weight factors affecting the spatial distribution of intra-field heterogeneity zones

Parameter and its designation	Ph	Po	Sa	Hu	Cu	Zn	B	Ca	Mg	Weight, W
Phosphorus (Ph)	0.35	0.42	0.40	0.35	0.31	0.27	0.24	0.22	0.20	0.31
Potassium (Po)	0.18	0.21	0.26	0.26	0.25	0.23	0.21	0.19	0.18	0.22
Soil acidity (Sa)	0.12	0.11	0.13	0.17	0.18	0.18	0.17	0.16	0.16	0.15
Humus (Hu)	0.09	0.07	0.07	0.09	0.12	0.14	0.14	0.14	0.13	0.11
Copper (Cu)	0.07	0.05	0.04	0.04	0.06	0.09	0.10	0.11	0.11	0.08
Zinc (Zn)	0.06	0.04	0.03	0.03	0.03	0.05	0.07	0.08	0.09	0.05
Boron (B)	0.05	0.04	0.03	0.02	0.02	0.02	0.03	0.05	0.07	0.04
Calcium (Ca)	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.03
Magnesium (Mg)	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02
Total	1	1	1	1	1	1	1	1	1	1

A relative weights matrix was built to determine the values of the relative weights of the parameters. (Table 5). To obtain it, the values from each column of the pair-wise comparison matrix were multiplied by the value of the weight of the corresponding parameter W (see Table 3), and the relative weight of each parameter W_i was calculated as the sum of the weights of the factor in each row of the matrix.

Table 5

Relative weights of the parameters affecting the spatial distribution of intra-field heterogeneity zones

Parameter and its designation	Ph	Po	Sa	Hu	Cu	Zn	B	Ca	Mg	Relative weight, W_i
Phosphorus (Ph)	0.31	0.44	0.45	0.44	0.40	0.30	0.28	0.24	0.18	3.04
Potassium (Po)	0.16	0.22	0.30	0.33	0.32	0.25	0.24	0.21	0.16	2.19
Soil acidity (Sa)	0.10	0.11	0.15	0.22	0.24	0.20	0.20	0.18	0.14	1.54
Humus (Hu)	0.08	0.07	0.08	0.11	0.16	0.15	0.16	0.15	0.12	1.08
Copper (Cu)	0.06	0.06	0.05	0.06	0.08	0.10	0.12	0.12	0.10	0.74
Zinc (Zn)	0.05	0.04	0.04	0.04	0.04	0.05	0.08	0.09	0.08	0.51
Boron (B)	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.06	0.06	0.35
Calcium (Ca)	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.04	0.24
Magnesium (Mg)	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.18

To confirm or refute the correctness of judgments about the magnitude of the influence of one or another soil parameter, the consistency of the weight matrix was assessed. At the first stage of the assessment, the eigenvalue of the consistency vector λ_{max} was determined as the quotient of dividing the total relative weight of each parameter W_i by the weight of the corresponding parameter W (Table 6).

Table 6

Calculation of the principal eigenvalue, λ_{max}

Parameter and its designation	Relative weight, W_i	Weight, W	Principal eigenvalue, λ_{max}
Phosphorus (Ph)	3.04	0.31	9.90
Potassium (Po)	2.19	0.22	10.01
Soil acidity (Sa)	1.54	0.15	10.00
Humus (Hu)	1.08	0.11	9.88
Copper (Cu)	0.74	0.08	9.70
Zinc (Zn)	0.51	0.05	9.56
Boron (B)	0.35	0.04	9.46
Calcium (Ca)	0.24	0.03	9.40
Magnesium (Mg)	0.18	0.02	9.44
The average value of the principal eigenvalue, λ_{max}	9.70		

According to Saaty [Saaty, 1980; 2008], for a pairwise comparison matrix to be consistent it must have a principal eigenvalue (λ_{max}) greater than or equal to the number of the parameters considered (n). The principal eigenvalue of 9.70 was obtained for the 9 x 9 matrix, hence the condition $\lambda_{max} \geq n$ is satisfied, and the pairwise comparison matrix is consistent.

To assess the overall inconsistency of the created hierarchical model, which is due to the accumulation of errors associated with the inconsistency of local judgments, the consistency index CI, (Equation (2)) and the consistency coefficient CR, (Equation (3)) were calculated:

$$CI = (\lambda_{max} - n) / (n - 1) \quad (2);$$

$$CR = CI / RI \quad (3),$$

where RI is a Random inconsistency index [Saaty, 1980].

The hierarchy is considered consistent if the value of CR does not exceed the level of 0.1 [Yeh et al., 2008]. In this study, for a matrix of nine variables, RI is 1.49, and the consistency coefficient is CR = 0.0591. This indicates that the weights assigned to the soil parameters are consistent and the hierarchical model is correct and structured in detail.

Discussions and results

As mentioned earlier, nine thematic layers with different soil parameters were used as initial geospatial data, which were obtained through the utilization of GIS (Figure 2).

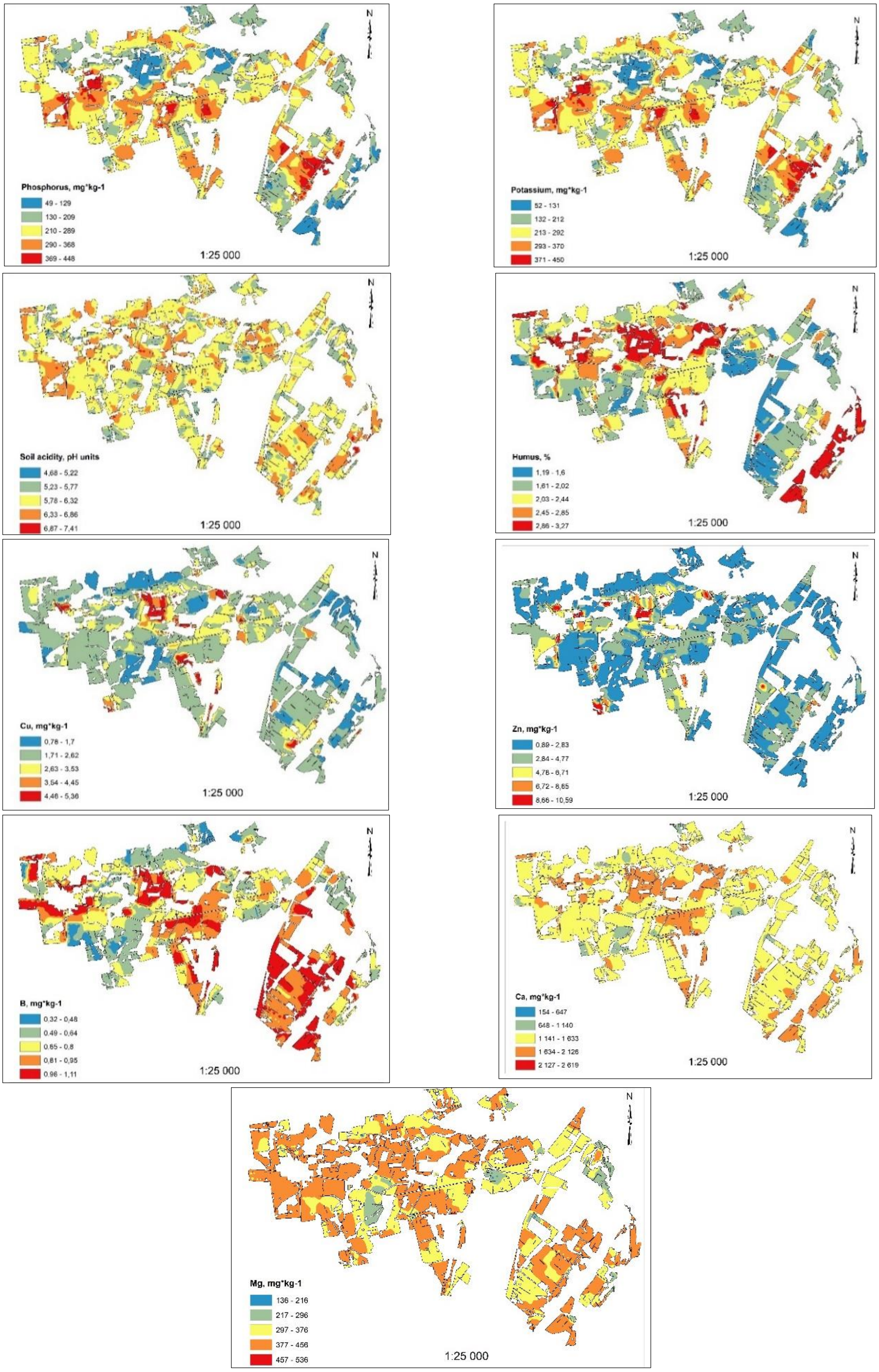

Fig. 2. Thematic layers with different soil parameters which were used to determine intra-field heterogeneity zones

The content of phosphorus and the content of potassium in the soil were determined as parameters with the highest influence weights. This is that because the identification of intra-field heterogeneity zones was carried out primarily to use its results for the off-line differentiated application of mineral fertilizers. In addition, these parameters are directly taken into account when calculating the norms of mineral fertilizers, the methodology for determining which is regulated by industry regulations that are mandatory for all agricultural entities in Belarus [Organizational and technological standards …., 2012a; 2012b]. The third most influential parameter is the acidity of the soil solution since this indicator is one of the most important factors in soil fertility and determines numerous features of the behavior of chemical elements in the soil ecosystem. The fourth most important place is occupied by the content of humus, which is one of the main indicators of soil quality, as well as carbon pools in the terrestrial ecosystem. This factor is considered important in environmental modeling, environmental forecasting, precision farming, and sustainable land use [Myslyva et al., 2017]. Further, in descending order of influence, the content of copper in the soil, the content of zinc, and the content of boron are located. Ranking within this group was carried out with the availability of soils with these elements, as well as the need for them in the main cultivated crops.
Values in the input raster layers were reclassified into a common evaluation scale of 1 (very low), 2 (low), 3 (satisfactory), 4 (good) and 5 (excellent). This was done by multiplying the cell values of each parameter class by the parameter weight and summing the resulting cell values to produce a map of intra-field heterogeneity zones [Senanayake et al., 2016], as summarized in Equation (4):

$$IFHZ = \sum_{i=1}^{n} W_i * R_i = (Ph_r Ph_w + Po_r Po_w + Sa_r Sa_w + Hu_r Hu_w + Cu_r Cu_w + Zn_r Zn_w + B_r B_w + Ca_r Ca_w + Mg_r Mg_w) \quad (4),$$

where IFHZ is the localization of the identified intra-field heterogeneity zones; W_i is the weight of each thematic layer, R_i is the rating of each class of each thematic layer; Ph, Po, Sa, Hu, Cu, Zn, B, Ca, Mn are soil parameters; the subscripts r and w refer, respectively, to the factor class of a thematic layer and its percent influence [Mageshkumar et al., 2019].
Figure 1 shows a general flowchart of the process of the identification of intra-field spatial heterogeneity zones, whose delineation is performed through the combined use of AHP and overlay analysis.

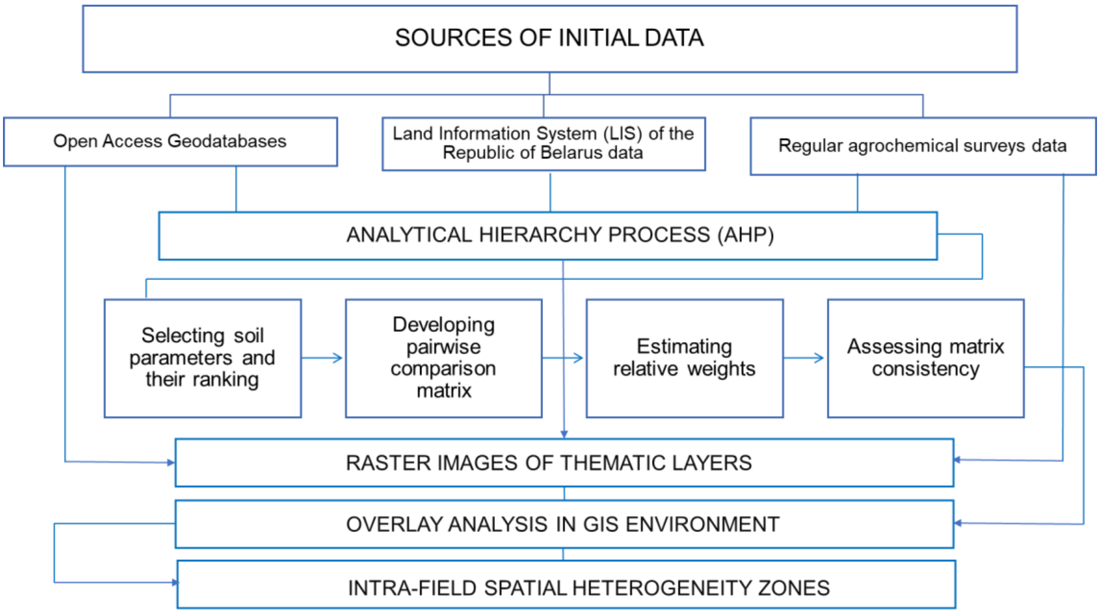

Fig. 3. Flowchart for intra-field spatial heterogeneity zones identifying

As a result of the identification of intra-field spatial heterogeneity zones, performed on the basis of estimates and weights of nine thematic layers with different soil parameters, a geoinformation model has been created (Equation 5).

$$IFHZ = 0.31Ph + 0.22Po + 0.15Sa + 0.11Hu + 0.08Cu + 0.05Zn + 0.04B + 0.03Ca + 0.02Mg \quad (5),$$

Raster images of the results of geoinformation model implementation are shown in Figures 4 and 5.

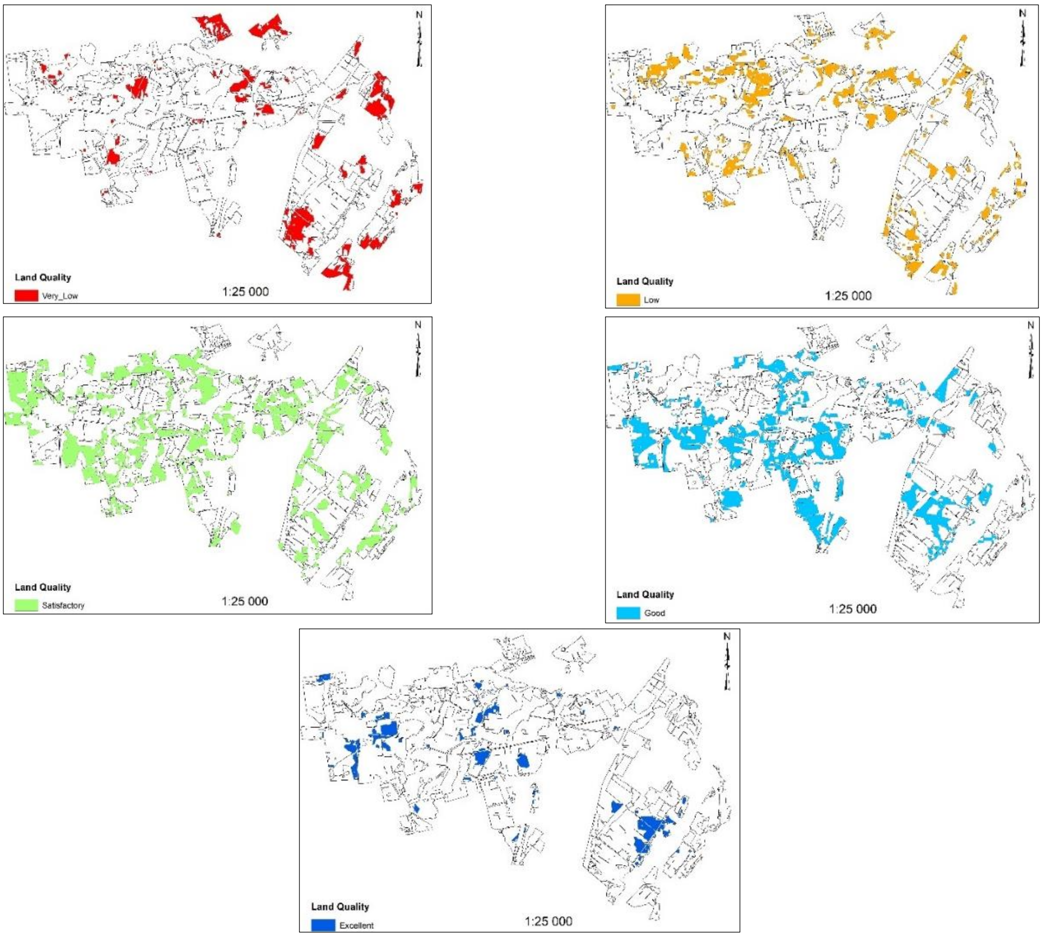

Fig. 4. Spatial localization of individual intra-field heterogeneity zones within the arable land of RPUE "Ustie" NAS of the Republic of Belarus

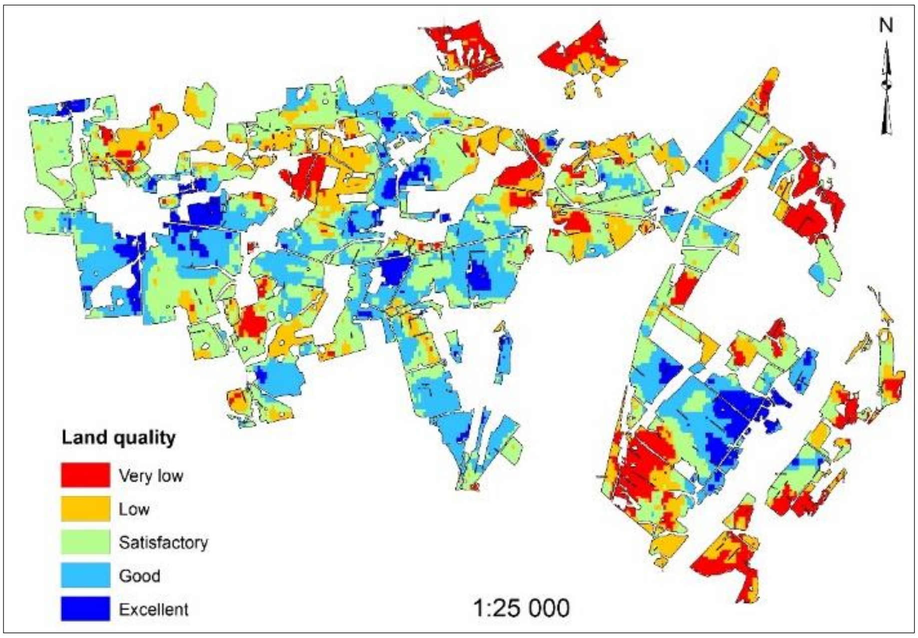

Fig. 5. Resulting raster of spatial distribution of intra-field heterogeneity zones within the arable land of RPUE "Ustie" NAS of the Republic of Belarus

(*Land with very low quality – 988.65 hectares; land with low quality* – 1385.99 hectares; *land with satisfactory quality – 2678.38 hectares; land with good quality – 1993.55 hectares; land with excellent quality – 502.92 hectares)*

Among the five identified zones with different land quality, the maximum share falls on land of satisfactory and good quality – 35.5% and 26.4%, respectively. At the same time, the area of land with very low quality is twice the area of land with excellent quality.

The use of the results obtained makes it possible to identify fertile and infertile areas within each individual field and differentiate the use of fertilizers in accordance with the provision of soil with nutrients, as well as more effectively plan the structure of sown areas. On the example of the RPUE "Ustie" NAS of the Republic of Belarus it was found that the use of dedicated intra-field heterogeneity zones for differentiated application of mineral fertilizers would reduce the total cost of purchasing and applying phosphorus fertilizers by 34 USD·ha^{-1} and potash fertilizers by 9 USD·ha^{-1} due to the redistribution of the fertilizer doses calculated for the planned yield. At the same time, the level of chemical pressure per hectare of arable land will decrease by 6.7% without loss of crops productivity (Table 7).

Table 7

Efficiency of intra-field spatial heterogeneity zones utilization to ensure differentiated application of mineral fertilizers

Characteristics of the created effect	**Amount of the created effect**		**The crop for which the maximum effect is recorded**
	%	USD·ha^{-1}	
Optimization of application rates and reduction of costs for the purchase of phosphate mineral fertilizers	12,8	5.3	Winter wheat
Optimization of application rates and reduction of costs for the purchase of potash mineral fertilizers	29,1	0.5	Sugar beet
Reducing the cost of applying phosphate mineral fertilizers	15,3	28.7	Winter wheat
Reducing the cost of applying potash mineral fertilizers	29,8	8.5	Sugar beet
Increasing the profitability of growing crops	1,35	–	Winter wheat
Reducing the level of chemical pressure on the soil	6,7	–	Winter wheat

Conclusions and proposals

The research results show that for the conditions of Belarus it is most expedient to determine ~~of~~ intra-field spatial heterogeneity zones based on data on the chemical properties of soils.

The AHP method, together with overlay analysis, makes it possible with a high probability to identify heterogeneities both within a single field and within the entire land use in several parameters.

The combination of these methods also makes it possible to establish clear boundaries between fertile and marginal lands, which can be used to determine site-specific management zones for precision farming, within which certain land management or agro-reclamation activities are planned.

The results of the study can also be used in other countries with agricultural organizations or farms with the land use area exceeding 500 ha.

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