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METHODOLOGY FOR DETERMINING SITE-SPECIFIC MANAGEMENT ZONES UPON IMPLEMENTATION OF PRECISION FARMING IN BELARUS

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Abstract
The aim of the study was to develop a methodology for determining homogeneous territorial zones for precision farming. In this study we took into account the national land use system which provides for the absence of private ownership of agricultural land. The algorithm for determining management-zones provides for: establishing zones of spatial heterogeneity; determining the presence of clusters and emissions; modeling the spatial distribution of soil quality indicators. 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 and soil pH. 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 individual field and differentiate the use of fertilizers, taking into account the presence of intra-field heterogeneity. This will save from 2.5 to 21.8 kg P ha^{-1} and from 0.9 to 26.7 kg K ha^{-1} due to the redistribution of the fertilizer dose calculated for the planned yield, taking into account the identified site-specific management zones. The differentiated use of mineral fertilizers will increase the profitability of growing winter cereals by 2.2%, sugar beets by 1.3%, rapeseed by 1.1%, and malting barley by 0.8%.
Key words: land management, management zones, geospatial analysis, precision farming, profitability.

Introduction

The presence of intra-field heterogeneity - the fundamental basis of precision farming is the result of a complex interaction of biological (pests, lumbricides), soil (salinity, organic matter, macro- and microelements, particle size distribution), anthropogenic (acidification, loss of organic matter, soil compaction, contamination with pesticide residues), topographic (slope, flow direction, flow accumulation) and climatic (relative humidity, temperature, precipitation) factors (Corwin at al., 2010; Heege, 2013; Myslyva, 2020). The identification of management zones (MZ) as one of the key components of precision farming - an agricultural management strategy aimed at maximizing the productivity and resistance of agricultural crops to unfavourable environmental factors through the optimal use of material and production resources, is carried out precisely by taking into account the intra-field spatial heterogeneity (Méndez-Vázqueza at al., 2019).

Despite the presence of a significant number of studies devoted to the identification of intra-field heterogeneity, a unified method for its determination has not yet been developed. Researchers propose different approaches to identify areas of spatial heterogeneity for precision farming purposes. They are usually based either on the use of yield maps (Yuxin Miao et al., 2018), or on the use of soil and topographic properties (Vitharana et al., 2008; Davatgar et al., 2012) and data on soil conductivity, remote sensing data, vegetation indices, or a combination of several types of data (Georgi et al., 2018; Shannon et al., 2018; Edge, 2019). Such a variety of approaches is due to the fact that when introducing precision farming, it is necessary to take into account a number of different factors that have significant differences in the context of individual climatic zones, countries, continents. In addition to choosing a method for determining management- zones, the question of their optimal number also remains unresolved. In particular, when cultivating corn for grain, American scientists recommend allocating two or three management zones within the field, using information on the content of the clay fraction in the soil, the slope of the territory, the content of soil organic matter, the value of the topographic moisture index and NDVI (Reyes at al., 2019). Other researchers recommend distinguishing from three to five management zones according to such indicators as the topography of the territory and the electrical conductivity of the soil when growing grain crops (wheat, soybeans, and grain sorghum) in conditions of insufficient moisture (Fraisse at al., 2001). An integrated approach to the determination of MZ for nitrogen application in corn and soybean growing using relative elevation, organic matter, slope, electrical conductivity, yield spatial trend map, and yield temporal stability map has been identified as the most appropriate in the studies of American scientists. At the same time, it is indicated that the optimal number of allocated MZ should be no more than three, which will provide the potential for economic return at the level of 19–55 USD/ha, depending on the zone (Yuxin Miao at al., 2018). German scientists proposed to use remote sensing data with a spatial resolution of 6.5 m to determine the zones of plant productivity according to the value of the vegetation index NDVI, which are advisable to use as potential management zones (Georgi at al., 2018). When introducing precision farming technology for growing grain crops, Pakistani scientists propose to identify four management zones, taking into account such indicators as the percentage of sand and clay fraction in the soil, the topography of the territory, the electrical conductivity of the soil and the nitrogen content (Farid at al., 2016). Researchers from Nigeria propose to distinguish four management zones according to a set of indicators, including: the content of total nitrogen and phosphorus, bulk soil density, carbon content, volumetric moisture, pH of the soil and its texture (content of sand, silt and clay) for the differentiated use of mineral fertilizers in growing vegetable crops (Oshunsanya at al., 2017).

The Republic of Belarus, which has just begun to introduce some elements of precision farming, in particular Variable Rate Technologies (VRT) also faced the problem of choosing both a method for determining zones of intra-field spatial heterogeneity and the optimal number of zones. Therefore, the purpose of this study was twofold: 1) to analyze the basic strategies for determining cite-specific zones and on the basis of their critical analysis, to develop methodological approaches and determine the parameters recommended for defining homogeneous management zones when introducing precision farming technology in the conditions of the Republic of Belarus; 2) to substantiate the methodological approaches for the use of geospatial statistics tools and develop a methodology for the formation of homogeneous territorial management zones in the process of on-farm land management for precision farming proposes.

Methodology of research and materials

Methods that were used in this research include analysis and synthesis method, a systematic approach method, abstraction, geostatistical and comparative research. The studies were carried out in 2017-2020 in such territories: 1) Gorky district of Mogilev region (Republic of Belarus) within the land use of RUE "Educational and experimental farm BSAA" on an area of 8342.1 thousand hectares of arable land (Figure 1); 2) Orsha district of Vitebsk region (Republic of Belarus) within the land use of RPUE "Ustye" NAS of the Republic of Belarus on an area of 7549.49 thousand hectares of arable land (Figure 2).

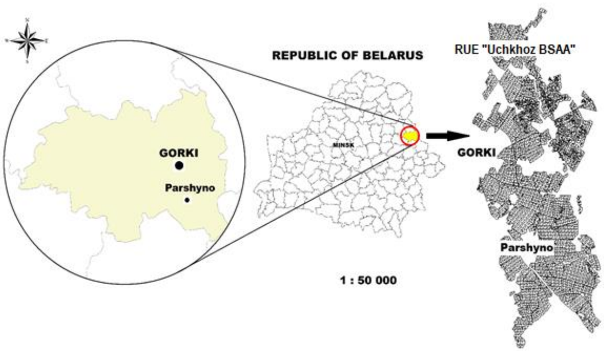


Fig. 1. The location of the studied territory of RUE "Educational and experimental farm BSAA"

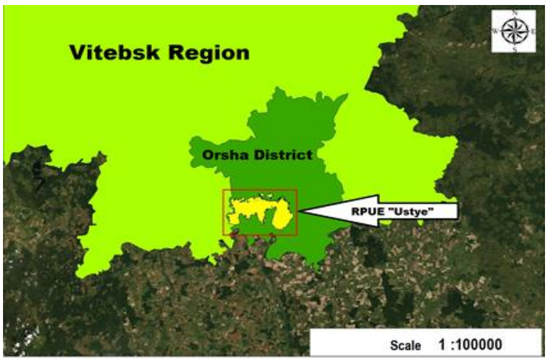


Fig. 2. The location of the studied territory of RPUE "Ustye" NAS of the Republic of Belarus

The climatic conditions of the study area are typical for the northeastern zone of the Republic of Belarus. The sum of active temperatures ranges from 2200 to 2400 degrees, and the average annual precipitation is 579 mm. The soil cover of the study area is represented by Sod-podzolic, Umbric Retisols (WRB, 2016); Eutric Podzoluvisol (FAO, 1988).

Agricultural enterprises on whose land use the research was carried out, specialize in dairy and meat production with developed grain production. The technologies they use for growing agricultural crops are generally accepted and are regulated by sectoral regulations that are binding on all subjects of agricultural activity on the territory of Belarus (Organizational and technological standards…. 2012a; 2012b).

The shape files with the placement of land within the study territories were created based on the results of digitization of planning and cartographic materials, which were obtained from the agrochemical survey of the territory of RUE "Educational and experimental farm BSAA", executed in 2018 by the Mogilev regional design and exploration station of agrochemicalization and the territory of RPUE "Ustye" NAS of the Republic of Belarus, executed in 2019 by the Vitebsk regional design and exploration station of agrochemicalization.

Identification of management zones and calculation of their areas within the study land use were carried out using the ArcGIS version 10.5.

The global Moran (I) index was calculated by the formula (1) (Mitchell, 2005):

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=i}^{n} w_{ij}(y_i-\bar{y})(y_j-\bar{y})}{[\sum_{i=1}^{n}\sum_{j=i}^{n} w_{ij}][\sum_{i=1}^{n}(y_i-\bar{y})^2]} \quad (1)$$

Where n denotes the number of units in the sample,

w_{ji} denotes the weight of the spatial relationship between the i-th and j-th sampling units,

y_i denotes the attribute value for the i-th sample unit,

$\bar{y}$ denotes the sample mean value of the attribute.

The Getis-OrdGi * index value was counted using the formula (2) (Mitchell, 2005):

$$\text{Getis-OrdGi*} = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \bar{X}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{[n\sum_{j=1}^{n} w_{i,j}^2 - (\sum_{j=1}^{n} w_{i,j})^2]}{n-1}}} \quad (2)$$

Where x_j denotes the attributive value of the object of observation,

$w_{i,j}$ denotes spatial weight between objects i and j,

n denotes the total number of objects.

Geospatial data analysis was used to pinpoint areas of spatial heterogeneity with low, fair, good and excellent land quality.

The economic efficiency of differentiated fertilization was carried out by determining the economic benefit of reducing the cost of purchasing and applying mineral fertilizers when growing individual crops. According to sectoral regulations documents (Organizational and technological standards…. 2012a; 2012b), the rates of fertilization for the planned yield of agricultural crops were calculated both for the entire area of the field and separately for each MZ defined within it. The costs for the purchase and application of mineral fertilizers, with and without taking into account intra-field heterogeneity, were calculated in a similar way. At the final stage, the profitability of growing crops using traditional and differentiated rates of mineral fertilizers was assessed.

Statistical processing of experimental data and the creation of mathematical models were carried out using Statistica version 13.0.

Discussion and results

The main task of modern land management in Belarus in the context of the introduction of precision farming is to develop a methodology for creating up-to-date digital maps and delineating land use territories by a set of land quality indicators. The market for similar products in the structure of elements of the precision farming system in the EU countries has grown by more than 17.5% over the past 5 years and is about 32% (Daheim et al., 2016), showing a steady upward trend (Aulbur et al., 2019).

The introduction of any element of the precision farming system should begin with the identification of management zones within the land use of agricultural organizations, which are more or less homogeneous not in one but in a number of indicators. In this regard the management zone in our opinion is a subsystem of precision farming and is a set of input parameters that are the basis for its determination and form a reaction as an economic effect that manifests itself in various aspects. On-farm land management is a universal tool for defining management zones and ensuring interaction between their input and output parameters. At the same time, the implementation of land management functions to define management zones should be carried out through the use of the functionality of geographic information systems. Moreover, the identification of site-specific management zones with the best and worst set of soil quality indicators (or other indicators, for example, the topography of the territory, agrophysical properties, productivity, values of vegetation indices) should be carried out as a mandatory measure within the framework of an on-farm land management (Figure 3).

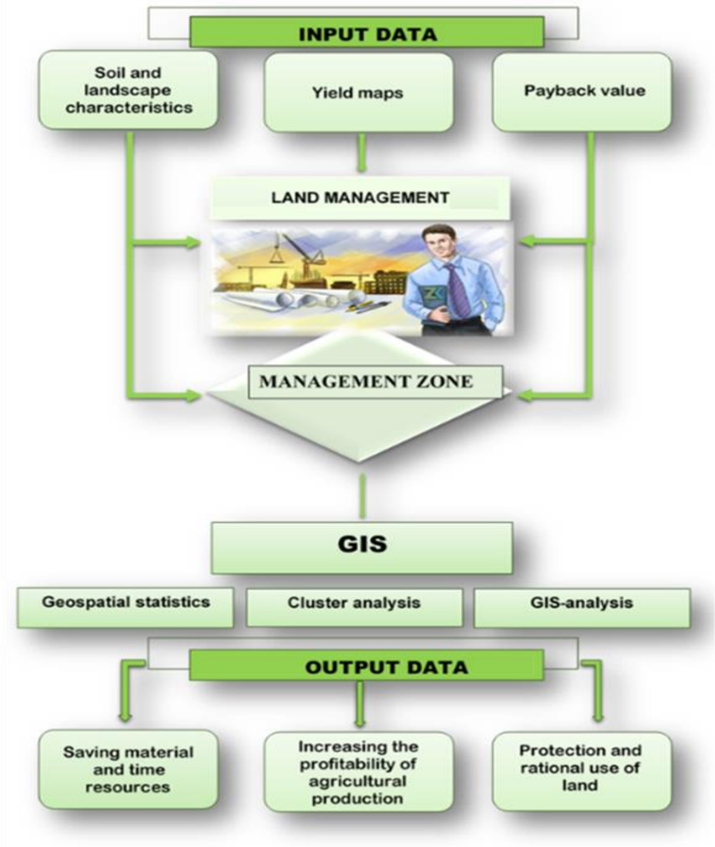


Fig. 3. The structure of the management zone as a subsystem of precision farming

In the future, the site-specific management zone should become an alternative to the use of elementary plots, which are the smallest spatial unit used in the implementation of on-farm land management and agrochemical survey of the land use area.

As mentioned earlier, today there are four main approaches to defining management zones: Approach 1: fields are divided into management zones in accordance with the values of one or more characteristics of the soil and landscape; Approach 2: determination of management zones is carried out using yield maps; Approach 3: management zones are determined by the value of the return on costs, primarily for the application of mineral fertilizers and plant protection products; Approach 4: integrated use of information about soil parameters or landscape characteristics and about the yield of agricultural crops or the return on costs of obtaining it.

The results of a critical analysis of these approaches as applied to the economic conditions of the Republic of Belarus indicate the following. Since elements of precision farming technology have just been introduced in Belarus, it is impossible to apply approach 3 based on economic characteristics. However, the definition of zones based on the values of soil parameters used in the US and EU countries (approach 1) and yield indicators (approach 2) also has a number of limitations. Based on this, when developing a methodology for determining management zones taking in regard the present conditions within the Republic of Belarus, the results obtained during an agrochemical survey of agricultural lands should be used as the initial ones. Data on soil chemical parameters are the results most often used by the agronomic services of agricultural enterprises. These parameters include, first of all, the content of humus, mobile phosphorus and potassium in the soil, as well as the pH of the soil solution. The list of recommended soil parameters can be expanded depending on the availability of geospatial data on soil properties and the requirements for defining management zones. In particular, it should contain information about the content of microelements in the soil, as well as the level of its contamination with pesticide residues, heavy metals and radionuclides.

The methodology has been developed for the identification of homogeneous territorial management zones for land management purposes when introducing precision farming (Figure 4). This technique has been tested within the land use of RUE "Educational and experimental farm BSAA" with an area of more than 8 thousand hectares.

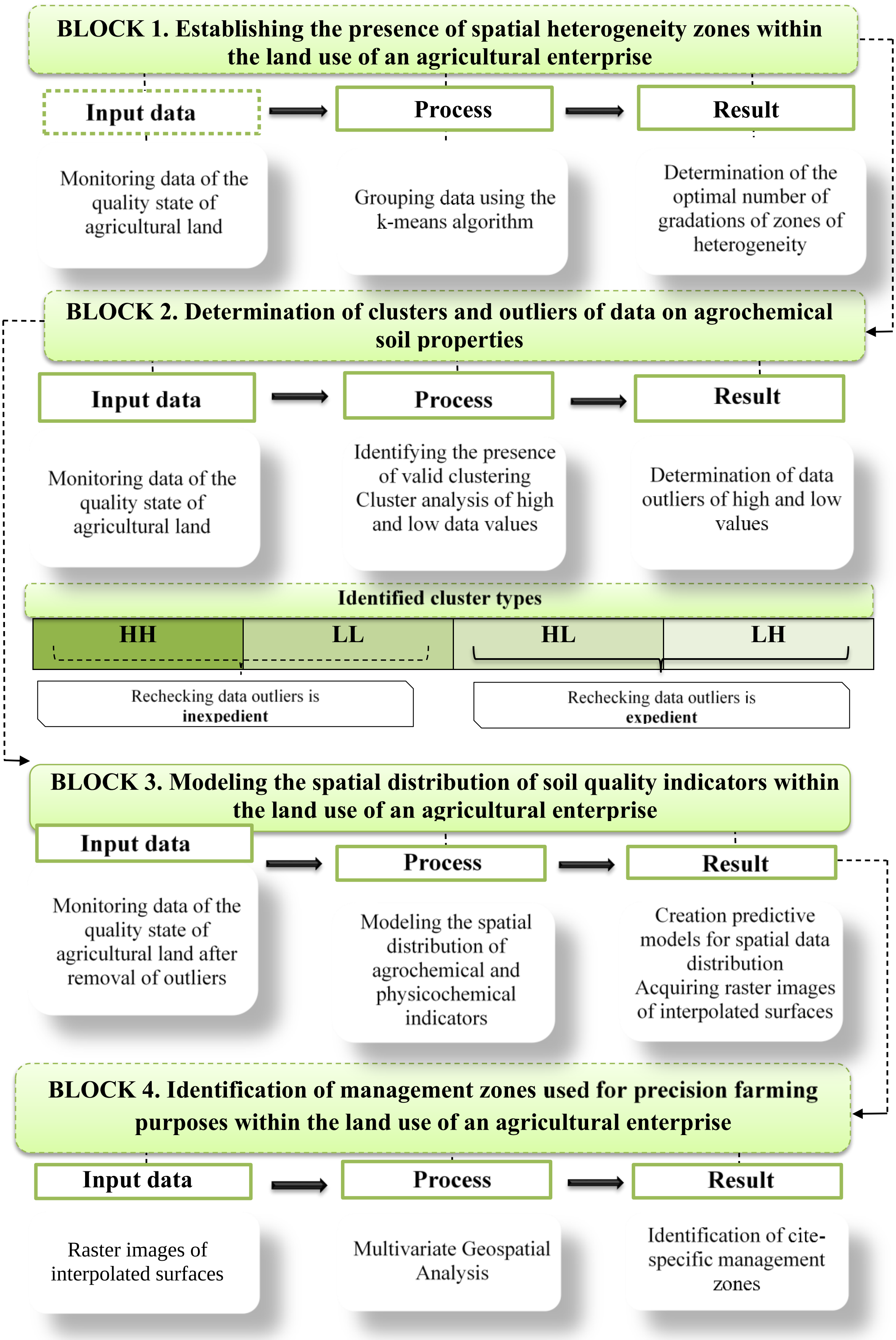


Fig. 4. Methodology for identifying cite-specific management zones with appropriate land quality (HL – cluster with high outliers; LH – cluster with low outliers)

The use of such a technique makes it possible to identify fertile and marginal areas within each individual field and to differentiate the use of fertilizers in accordance with the supply of nutrients to the soil. This technique also makes it possible to more efficiently plan the structure of sown areas. In the example of the RUE "Educational and experimental farm BSAA" it was found that on the area of 1411.76 ha it is possible to save from 2.5 to 21.8 kg P ha^{-1} and from 0.9 to 26.7 kg K ha^{-1} due to the redistribution of the dose of fertilizers for the planned crop yield, taking into account the identified management zones. The maximum saving of phosphorus fertilizers is achieved when applying them for winter wheat, corn for silage and peas grown for grain while potash fertilizers provide maximum saving when applying them for winter wheat, sugar beets and spring triticale.
The differentiated use of mineral fertilizers by reducing the cost of their purchase and use makes it possible to increase the profitability of growing winter grains by 2.2%, sugar beets by 1.3%, rapeseed for oilseeds by 1.1%, and malting barley by 0.8% (Table 1). The maximum saving of fertilizers is achieved when they are used under wheat cereals, spring cereals and rape. Hence the differential fertilizer application should be introduced primary for growing these crops.

Table 1

Economic efficiency of off-line technology of differentiated application of fertilizers

Agricultural crop	**Reducing the cost of purchasing fertilizers, BYN/hectare***		**Reducing the cost of applying mineral fertilizers, %***	**Profitability, %**
	P_2O_5	**K_2O**		
Winter wheat	30.94	0.18	20.8	2.2
Malting barley	14.19	0.99	11.1	0.8
Rapeseed	3.63	1.32	6.5	1.1
Sugar beets	4.79	5.28	7.0	1.3

Note: * compared to a traditional fertilization system, recommended by sectoral regulations documents (Organizational and technological standards…. 2012a; 2012b)

The implementation of the methodology for management zones identification of block 3 and block 4 tasks in Fig. 4, are described in detail in (Kutsayeva & Myslyva. 2020). In addition, the specificity of land use in Belarus, which provides for the concentration of agricultural land in state ownership (Myslyva, 2020), allows land surveyors to use a significant array of data on soil properties, which are obtained during planned rounds of agrochemical research. These data can and should be scrutinized with spatial statistics tools to enable further accurate identification of the site-specific management zone boundaries.
In particular, the implementation of the first block of tasks of the developed methodology provides for the determination of the optimal number of land quality gradations or the establishment of the optimal number of zones of spatial heterogeneity. Unfortunately, there is no single standard to establish the optimal number of zones of heterogeneity it will always differ. In each specific case it should be established based on the available geospatial data and their statistical characteristics, also taking into account the features of the relief of the land use area.
For example, within the land use RUE "Educational and experimental farm BSAA", the presence of four zones of spatial heterogeneity was established on the basis of a complex of 4 agrochemical indicators. At the same time, for land use RPUE "Ustye" NAS of the Republic of Belarus, the presence of 3 zones of heterogeneity was established on the basis of a complex of 9 agrochemical indicators. The optimal number of such zones is most rationally determined empirically by evaluating the output report on the results of grouping analysis using the k-means algorithm. Grouping efficiency can also be assessed using the Calinski-Harabasz pseudo-F-statistics (Calinski & Harabasz, 1974). This indicator reflects the similarity of objects in a group and the difference between groups and indicates the correctness of choosing the optimal number of heterogeneity groups (Figure 5).
Cluster analysis, provided by the second block of tasks of the methodology, should be performed in parallel with the grouping analysis. The results obtained should complement each other and ensure the possibility of making the only correct decision on the final identification the boundaries of site-specific management zones. First of all, it seems possible to determine the fact of the presence of spatial data clustering. This can be accomplished by calculating the nearest neighbor index value, which takes into account the coordinates, rather than the values of the control points attributes.

If this clustering type is set, the next step is to perform stepwise autocorrelation, which allows you to select a conceptual model of spatial relationships and set a threshold distance beyond which the mutual influence of neighboring objects is not taken into account. The obtained information can be used to establish the fact of the presence of clustering of attribute values at the control points, which is established by calculating the global Moran's index. If the value of the global Moran's index is greater than 1, this indicates the presence of clustering, and the next step should be to establish which values are clustered - high or low. This fact can be established by calculating the value of global Getis-Ord General G.

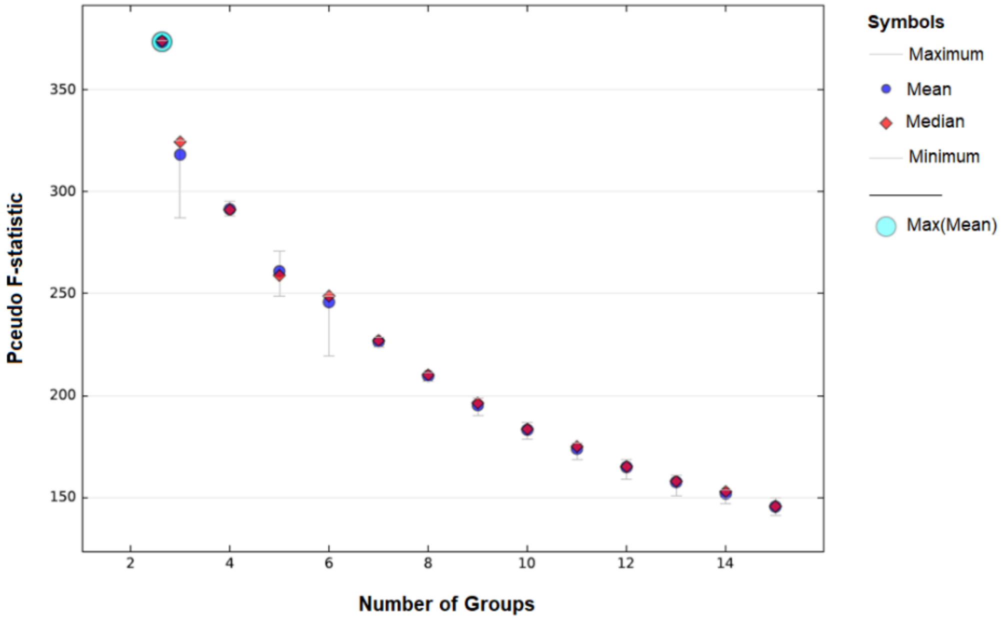


Fig. 5. Pseudo F-statistic plot (determining of spatial heterogeneity zones for the land use territory of RPUE "Ustye" NAS of the Republic of Belarus)

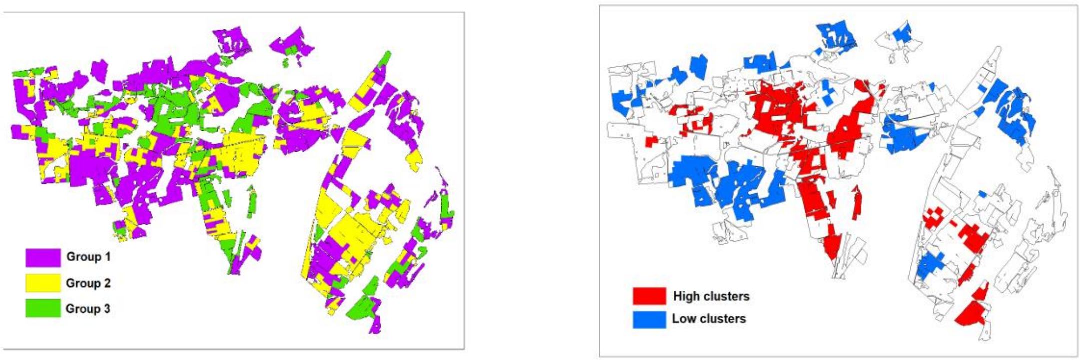
When clustering of both high and low values is present, their clustering is canceled out. Therefore, it is necessary to conduct a hot spot analysis. This allows not only to establish the presence of data clustering with high and low values, but also to assess the statistical significance of the identified clusters. This analysis is done by defining the Getis-Ord Gi *, a statistic that is calculated for each feature in the dataset. However, it should be noted that when calculating this indicator, not the attribute values of individual objects are taken into account, but the attribute values of their environment. These values are calculated for each object and compared with the values in the rest of the study area.

If significant clustering of high and low values is found, cluster and outlier analysis should be performed by determining Anselin Local Moran's I value. This analysis identifies concentration of high values, concentration of low values and spatial outliers of geospatial data. If, as a result of the cluster analysis, the presence of clusters of the high-low (HL) and low-high (LH) types is established, this indicates that spatial outliers of high (HL-clusters) and low (LH-clusters) values presents within the study area.

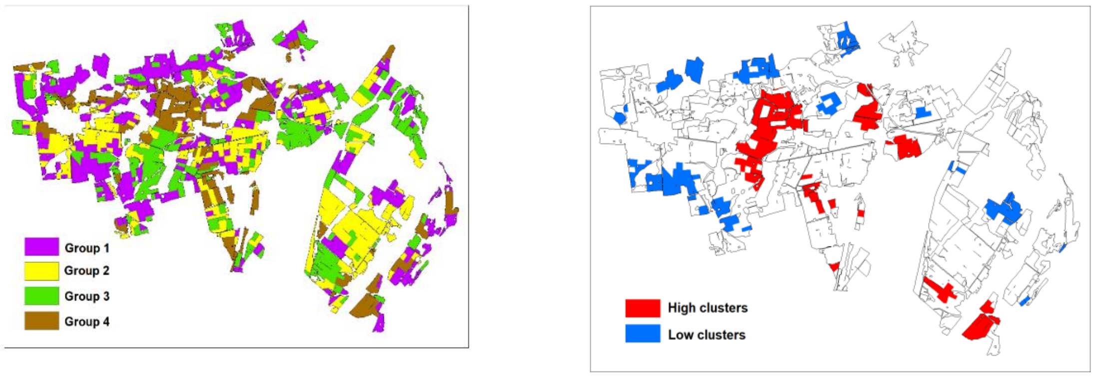
Performing cluster analysis is closely related to group analysis. Figure 6 shows the spatial localization of the identified groups - zones of spatial heterogeneity, as well as the result of cluster analysis, in the process of which statistically significant zones of concentration of high and low values of data on agrochemical and physicochemical properties of soil were identified.

The best ratio "cluster homogeneity - group homogeneity" was established when combined into three groups. With such a number of groups, the maximum coincidence was recorded for the localization of the lands of the 1st group with the localization of low clusters and for the localization of the lands of the 3rd group with the localization of high clusters. The area of land that belongs to group 1 was 3881.04 hectares, to group 2 - 2214.63 hectares, to group 3 - 1453.83 hectares, which in percentage terms was 51.4, 29.3 and 19.3% to the total land use area, respectively. When performing the identification of five groups, groups 3, 4, and 5 localize in the high clusters area while groups 1 and 2 - in the low clusters area. This indicates the inexpediency of separating such a number of groups. A similar trend is observed when performing division into four groups.

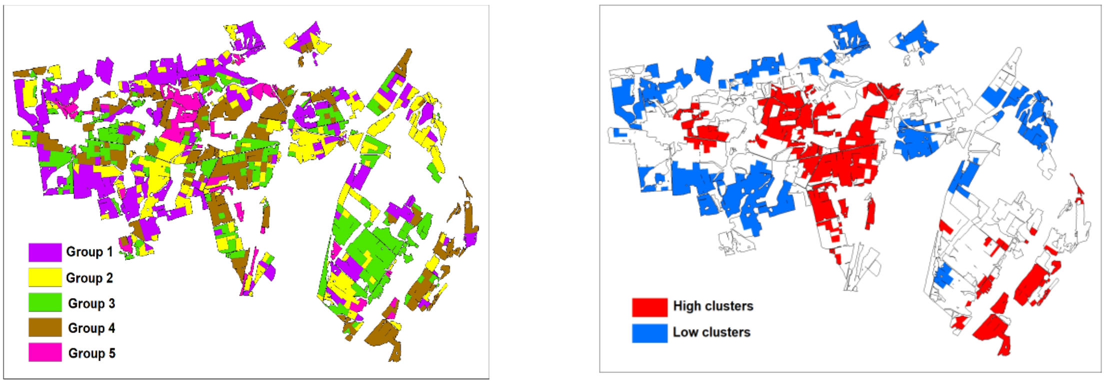
It should be specially noted that the implementation of the first two blocks of tasks is necessary and is an integral part of the identification process of management zones, since we are talking about developing a use strategy for significant land areas. This is due to the fact that according to statistics (Agriculture of the Republic…, 2019), an average land use of agricultural enterprise in Belarus contains more than 5.3 thousand hectares of agricultural land and over 3.5 thousand hectares of arable land.



a)



b)



c)

Fig. 6. Spatial localization of the identified groups - zones of spatial heterogeneity and the result of the cluster analysis within the arable land RPUE "Ustye" NAS of the Republic of Belarus
(***for a***: *group 1 – land with low quality; group 2 – land with satisfactory quality; group 3 – land with good quality;* ***for b***: *groups 1–3 – see gradation for a; group 4 – land with excellent quality;* ***for c***: *1 – land with very low quality; group 2 – land with low quality; group 3 – land with satisfactory quality; group 4 – land with good quality; group 5 – land with excellent quality)*

Conclusions and proposals

The research results show that for the conditions of Belarus it is most expedient to determine the management zones on the basis of data on the agrochemical properties of the soil.

Geospatial statistics methods make it possible with a 99% probability to identify heterogeneities within an individual field, as well as the entire land use by one or more parameters. They also make it possible to establish clear boundaries between fertile and low-fertile lands. This can be used to determine management zones for precision farming purposes, within which certain land management activities are planned to be carried out.

The algorithm for determining the management-zones provides the sequential performance of the following operations:

- exploration geostatistical analysis;
- determination of the required number of gradations of land quality;
- assessment of data clustering and analysis, search for data outliers;
- construction of interpolated raster surfaces for a specific set of soil parameters;
- reclassification of rasters and multivariate analysis;
- converting the final raster into vector layers and determining the areas of the selected zones.

As input parameters, it is recommended to use the data of agrochemical soil survey performed centrally every 4 years for every agricultural enterprise.

The results of performing differentiation of management zones can be used for planning differentiated application of mineral fertilizers, which will save resources and improve the agrochemical, physical and biological properties of the soil.

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