GIS-BASED MULTI-CRITERIA ANALYSIS OF THE SUITABILITY OF WESTERN SIBERIAN FOREST-STEPPE LANDS

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ABSTRACT
The main purpose of this work is to assess the suitability of land for cultivation of the main agricultural crop of Western Siberia, namely spring wheat. The algorithm of land suitability assessment was developed on the territory of the test plot of land-use of CJSC Mirny, Kochenevsky District, Novosibirsk Region. For assessment of land suitability on the basis of expert knowledge, criteria related to relief and soil, not only known but also specific, inherent in the area under consideration, have been identified. In the absence of information on the topography and relief of the territory under consideration, the spatial database of geodata was created based on the results of high-resolution digital aerial photography from an unmanned aerial vehicle (UAV). Elementary surfaces (ESSs) at the micro-relief level have been determined with the help of GIS tools. Two most popular methods of obtaining criterion weights have been analysed: Analytic Hierarchy Process and the direct ranking method, and under certain conditions, a connection between these methods have been established. To assess the land suitability, the land suitability indices of selected ESSs were calculated using GIS-MCDA (Multiple-Criteria Decision Analysis) method Weighted linear combination. Based on the value of land suitability index for all ESSs, belonging to a certain suitability class according to FAO classification has been established. A map of land suitability with an assessment of spring wheat sowing expediency was obtained.

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1. Introduction
Spring soft wheat in Siberia is the main food crop and is sown on an area of about 5.4 million hectares, which is more than 44% of the total spring-sown area. This crop requires nutrients in an accessible form in the soil, which is due to the short growing season (100–120 days) and the reduced absorption capacity of the root system. The best for it is considered to be the chernozem type soils with high potential fertility and characterized by neutral or slightly acidic pH, high humus content, increased nitrification capacity and availability of mobile forms of phosphorus and potassium, favourable volume weight, as well as good moisture capacity of the metre layer of soil. Soil types are specified according to the Russian soil classification. It is not recommended to cultivate wheat on sandy soils of pine terraces, on not meliorated salt marshes and saline, on waterlogged meadow-bog soils and sod-gley soils.

Typical natural features of Siberia are harsh climatic conditions (sharply continental climate), a large variety of natural zones and landscapes that replace each other in a small geographical space, the diversity of the soil cover, low soil fertility. On the territory of a particular land-use (farm) in the soil cover, it can occur up to 100 varieties of soils, characterized by complex structure and contrast. All this complicates the production of crop products, including spring wheat grains.

Under these conditions, it becomes very important to properly place wheat crops on the land favourable for its cultivation, contributing to the realization of the biological potential of this crop yield and reducing the technological costs. For on-farm differentiation of crop placement, it is important to consider as many land-use features as possible. At present, however, farms mainly use medium resolution maps (1:10,000, 1:25,000), which does not allow for more accurate land cover and relief accounting. Therefore, it is relevant to create maps in a GIS environment of higher resolution, for example, 1:1000 using remote sensing from space or an unmanned aerial vehicle (UAV) aerial survey.

Land assessment for the cultivation of agricultural crops in Russia has a long tradition. This section of soil science, founded by the works of V. V. Dokuchayev of the second half of the nineteenth century, developed from appraisal of soil (Sibircev 1951), evaluation of the productivity of soil-agroecological properties (Karmanov and Bulgakov 2007) to agroecological assessment of lands (Kiryushin and Ivanov 2005). These estimates are
based on parametric statistics and correlations between soil, climate and other conditions with crop yields. The FAO land valuation methodology and approaches were also used (FAO 1976), which assesses the suitability of land for crops in terms of suitability ratings (from very suitable to unsuitable), which in Russia are expressed in the form of agricultural production groups.

The choice of the most appropriate algorithm for assessing land suitability is important for current and future land-use planning, as well as the ability to automate this process by integrating GIS, UAV and MCDA technologies. The key stage of assessing the suitability of lands for spring wheat sowing is determining the weight of a certain factor affecting the suitability of a particular land plot. The large number of these factors, which also have different levels of significance, makes it difficult to assess the suitability of land (Rozhkov 2014).

According to many researchers (Nguyen 2017; Kahsay et al. 2018; Dedeoğlu and Dengiz 2019; Herzberg et al. 2019; Layomi, Kumar, and Sandamali 2019; Radočaja et al. 2020), despite some limitations, Analytic Hierarchy Process (AHP) is still the most commonly used method for determining weights of criteria for subsequent assessment of land suitability for certain crops, especially on a small scale. Land-use plans and agro-technologies, which do not take into account natural resources, limit crop yields and increase production costs (El Baroudy 2016; Tadesse and Negese 2020). Therefore, an actual task remains to develop methods for determining various indices for subsequent assessment of land suitability for certain crops in order to ensure sustainable agricultural production (Akpoti, Kabo-bah, and Zwart 2019). Identification of suitability classes with homogeneous characteristics is a fundamental segment of land assessment that allows for effective land-use planning (FAO 1976). Mapping these crop suitability classes is important for transferring knowledge to end-users to reduce land degradation and assess sustainable land-use (Joerin, Thériault, and Musy 2001; Collins, Steiner, and Rushman 2001). However, there are still gaps in local knowledge related to the impacts of land management, in particular those anthropogenic changes in landscapes that reduce or eliminate land cover and agricultural land degradation (Erb et al. 2017).

The integration of GIS and multicriteria analysis of solutions is discussed in detail in (Malczewski 2004, 2006), where the researchers are undoubtedly interested in spatial solution methods associated with a large number of possible alternatives and multiple, controversial and inconsistent evaluation criteria. Many decision-making problems can be supported by the multifactor analysis of GIS-MCDA-based solutions. More recent work, such as (Greene et al. 2011), provides detailed background information for GIS users, analysts and researchers to better understand MCDA, including for decision-makers.

From all the above we can conclude that the integration of MCDA using GIS is a current trend in land suitability analysis. In Russia this approach is practically undeveloped, we do not know any publications on this problem. At the same time, this approach to selecting alternatives for land assessment and decision support is widely discussed in world literature (Li et al. 2012; Zhang et al. 2015; Yalw et al. 2016; Kahsay et al. 2018).

The result of our research is important because it provides rational approaches to increase land-use efficiency and better management for spring wheat grain production.

The research was conducted with the objectives:
1) To assess the suitability of land for spring wheat grain production in the forest-steppe zone of Western Siberia.
2) To study the possibilities of using GIS and MCDA integration to obtain reliable information on land for spring wheat grain production.

2. Study area and methods
2.1. Study area

The research was conducted in the forest-steppe zone of the Novosibirsk Region in the West Siberian Plain. The climate of the plain is sharply continental, characterized by severe long winters and short summers with uneven rainfall. Landscapes of the forest-steppe zone are formed under the conditions of flat terrain. In terms of geomorphology, the area is a weakly drained plain with absolute altitudes of 110 to 280 m above the Baltic Sea level, complicated by slight slopes. The ravines and troughs formed as a result of erosion activities are confined to the river banks. There are also numerous hollows filled with ponds and lakes. Under weakly drained conditions, saline palaeogene and neogene deposits are close to each other, causing salinization of soils and wide distribution of saline and salt marshes.

The object of research was a test plot on the territory of land-use of CJSC ‘Mirny’ of Kochenevsky district of Novosibirsk region (54°56′24″ N; 82°06′16″ E; 54°55′07″ N; 82°09′27″ E, 54°54′26″ N; 82°07′40″ E, 54°55′29″ N; 82°05′12″ E, which is a typical forest-steppe zone land plot (Figure 1)).

The soil cover of the test plot is diverse, there are common chernozem, meadow-chernozem, grey forest, meadow, swamp and other soils. Swamp soils lie along the banks of the Sharikh River and ponds. Birch spikes,
which are small amounts of woody vegetation, are widespread in the study area.

2.2. Methods

2.2.1. GIS data analysis

To assess the suitability of agricultural land, GIS technologies were used, which made it possible to integrate the capabilities of geospatial data acquisition, geocoding and processing. In general, the data analysis process can be divided into three main stages (Figure 2).

The first stage is related to the formation of the DSLM (Digital spatial land-use model), which includes the cartographic and attributive parts of the geodatabase of GIS. Consistency of cartographic, remote and field observations is achieved by setting a unified cartographic projection and geodetic coordinates system in the process of spatial reference of GIS layers. For the semantic description the object-relational model of the data in which the basic information units serve spatial classes, objects of a class and mutual relations between objects of a class are used. The following spatial classes have been used in the work: Relief, Soils, Hydrography, Vegetation, Land areas.

The second and third stages of land suitability assessment are related to geo-information and multi-criteria analysis of spatial data. Within the framework of geoinformation analysis, the following tasks were solved: a selection of the smallest territorial units, their description and division into suitability classes using multi-criteria analysis.

ESs (Elementary surfaces) was adopted as the smallest territorial units for mapping and assessment of the suitability of agricultural lands. According to (Lastochkin 2002), ESs are relatively homogeneous morphologically areas of the Earth’s surface, where approximately the same processes of transformation of matter and energy occur.

Remote sensing of the plot was performed by Supercam S250F UAV. As a result of photogrammetric processing of digital images, the following tasks were solved: the point positions from pixel coordinate system into terrain coordinate system were transformed, and then on this data digital irregular (TIN, Triangulated Irregular Network) and regular (DEM) surface models, textured terrain models (TTM) and orthophoto plans were constructed.

Aerial photographing of the study area was carried out in October 2018 after harvesting crops, and in the spring 2019 after the snow melting and spring tillage before sowing, at a height above the underlying surface of 170 m, with a cross overlap between the images of 40% and longitudinal overlap 60%, which allowed to build 3D-textured surfaces, TIN and GRID-models of relief with 0.10 cm spatial resolution. The resulting orthophotoplane served as the basis for DSLM (M 1:1000), which was created using a fully functional ArcGIS10.

The cartographic part of the geodatabase is represented by raster and vector models taking into account the coordinate georeferencing of soil maps,
agrochemical survey maps and orthophotoplane. A digital soil map was created using a digital elevation model (DEM) and soil survey results (Pavlova, Kalichkin, and Kalichkin 2019).
2.2.2. Criteria for multi-criteria data analysis

The main criteria for assessing land suitability are indicators reflecting geomorphological, soil conditions and negative factors affecting land productivity.

The following criteria related to relief and soil were chosen: $X_1$ – slope; $X_2$ – slope exposure, $X_3$ – granulometric composition, $X_4$ – capacity of the humus horizon, $X_5$ – erodibility, $X_6$ – salinity, $X_7$ – drainability, $X_8$ – micro-drainage contouring.

All the above criteria were selected on the experts’ opinion, based on the conditions typical for Western Siberia. Not only known factors such as slope and slope exposure are used but also limiting factors such as salinity and erodibility.

In the conditions of the gently undulating plain, micro-drainage flows are widespread, which are displayed on a large-scale orthophotoplan due to the high spatial resolution. Micro-drainage flows have elongated shape and depth, cut into the most suitable land, complicating soil cultivation. Therefore, contouring has been chosen as one of the criteria for assessing land suitability.

Each criterion can affect wheat yields in different ways, so the selected criteria should be ranked and given certain weights according to their importance.

2.2.3. Finding the weights of the criteria

The weight of the criteria can be determined in various ways. For example, they can be calculated if long time series are known from which the impact of criteria on crop yields can be analysed. But in practice, such data are either not available or they are incomplete.

If all criteria are equally important, their weights are determined by a formula $w_i = \frac{1}{n}$, where $i = 1, \ldots, n$, $n$ is the number of criteria. Sometimes a formula for calculating criterion weights is associated with arithmetic or geometric progression. A review of some approaches to selecting criteria weights is given in (Odu 2019). In our work, we consider two, in our opinion, the most common methods for determining criterion weights, the ‘direct ranking method’ and ‘AHP’ and under some conditions show the relationship between these methods, a fact that seems to be noticed for the first time.

2.2.4. Direct ranking method

This method involves a group of experts.

Let $n$ criteria $X_1, X_2, \ldots, X_n$ be chosen and $m$ experts $E_1, E_2, \ldots, E_m$ be involved to rank these criteria. In other words, the task is to arrange the criteria, for example, in decreasing order of importance (from most important to least important). The experts evaluate each criterion and these evaluations are added to the table, Table 1,

| Table 1. Expert evaluation of each criterion (in general terms). |
| $E_i$ | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $r_{i1}$ | $r_{i2}$ | $r_{i3}$ | $r_{i4}$ | $r_{i5}$ | $r_{i6}$ | $r_{i7}$ | $r_{i8}$ |
| $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ |
| $r_{n1}$ | $r_{n2}$ | $r_{n3}$ | $r_{n4}$ | $r_{n5}$ | $r_{n6}$ | $r_{n7}$ | $r_{n8}$ |

where $r_{ij}$ is the $i$-th expert’s assessment of the importance of the $j$-th criterion. This estimate is measured by a natural number in the range of $[1, n]$. The proximity of $r_{ij}$ to $n$ shows that the expert highly evaluated the $j$-th criterion; experts are not required to use the numbers from 1 to $n$ exactly once in their assessments, the number can be repeated.

Next, the sum of estimates of all experts for each criterion (sum up the columns elements) is calculated:

$$R_j = \sum_{i=1}^{m} r_{ij}, \ j = 1, \ldots, n.$$  

It is already possible to rank the criteria by the found indicators $R_j$; the largest indicator $R_j$ corresponds to the most important criterion, etc.

We also calculate the sum of all experts’ estimates by all criteria

$$R = \sum_{j=1}^{n} R_j = \sum_{j=1}^{n} \sum_{i=1}^{m} r_{ij}$$  

and get the weights for the criteria ordered by importance using the following formulas:

$$a^{(1)} = \max_{j=1 \ldots n} \frac{R_j}{n}, \ldots, a^{(n)} = \min_{j=1 \ldots n} \frac{R_j}{n}.$$  

Obviously, that $\sum a^{(l)} = 1$. However, it is necessary to analyse the consistency of expert opinions in order to conduct further research based on the criteria weights. To do this, the Kendall concordance coefficient (W) is calculated and the statistical Pearson’s chi-squared test ($\chi^2$) is applied.

The Kendall concordance coefficient is found by the formula

$$W = \frac{12S}{m^2(n^3 - n) - m^2 \sum_{j=1}^{m} T_j},$$

where $m$ is the number of experts, $n$ is the number of criteria, $S = \sum_{j=1}^{n} \left( R_j - n \right)^2$, $T_j = \sum_{i=1}^{m} \left( t_i^3 - t_i \right)$. Among the set of evaluations assigned by the $j$-th expert, the number of groups $l$ that have the same evaluations is determined, $t_i$ is the number of such identical evaluations for each of the $l$ groups.

We consider the following hypotheses:  
$H_0$: expert opinions are not consistent;  
$H_1$: expert opinions are consistent.
It is known (Kendall 1970) that if the hypothesis $H_0$ is correct; then, the distribution of a random variable $\chi^2 = m(n-1) \cdot W$ at sufficiently large $n$ is close to the chi-square distribution with $(n-1)$ degrees of freedom (denote it $\chi^2(n-1)$). Therefore, we can do the following: define the significance level $\alpha$, i.e. the probability of error of the first kind (the probability that we will reject the hypothesis and it will be true), by the table we find $\chi^2_{\alpha} = \chi^2_{1-\alpha}(n-1)$ the $(1-\alpha)$-quantile of $\chi^2(n-1)$ distribution. And then use the following criterion:

if $\chi^2 > \chi^2_{\alpha}$, then we reject the hypothesis $H_0$ and consider that the experts’ opinions have been consistent;

if $\chi^2 \leq \chi^2_{\alpha}$, then we accept hypothesis $H_0$ and consider that the experts’ opinions have not been consistent.

### 2.2.5. AHP (Saaty 1980)

For the $n$ selected criteria $X_i$, $j = 1, \ldots, n$, a pairwise comparison matrix of criteria of the form

$$A = \begin{pmatrix}
1 & a_{12} & \ldots & a_{1n} \\
1/a_{12} & 1 & \ldots & a_{2n} \\
& \ldots & \ldots & \ldots \\
1/a_{1n} & 1/a_{2n} & \ldots & 1
\end{pmatrix}$$

is constructed (Kou et al. 2016). Here $a_{ij}$ is the number that characterizes the judgement of a pair of criteria $X_i$ and $X_j$. If the criteria are of equal importance, then $a_{ij} = a_{ji} = 1$.

$A$ is a positive and inversely symmetric matrix. The values of the elements $a_{ij}$, where $i < j$ (i.e. elements above the main diagonal) are selected based on the fact that the criterion $X_i$ in a certain way exceeds the criterion $X_j$ (if $i$ is a row number, $j$ is a column number). In (Saaty 1980) it is proposed to determine the degree of preference or significance of one criterion over the other using degree values from 1 (in case of equal importance) to 9 (in case of absolute importance). Thus, only numbers 1, 2, 3, 4, 5, 6, 7, 8, 9, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9 can be elements of the pairwise comparison matrix $A$.

However, there are works that use other numerical values to determine the degree of preference for criterion pairs (Zolekar and Bhagat 2015; Kumar et al. 2019).

Matrix $A$ is called consistent if

$$a_{ij} = a_{ik} \cdot a_{kj}$$

for all $i, j, k$. If the matrix is consistent, it will also be transitive (if the criterion $X_i$ is more significant than $X_{i+1}$, $X_{i+1}$ in turn, is more significant than $X_{i+2}$, then $X_{i+2}$ should not be more significant than $X_i$). The positive

inversely symmetric matrix is consistent if and only if $\lambda_{\max} = n$, where $\lambda_{\max}$ is the largest eigenvalue of matrix $A$ (Saaty 1980).

If only the above-mentioned numbers are used in the pairwise comparison matrix $A$, it is obvious that the consistency property (1) for matrix $A$ will not be satisfied in most cases. But if the elements of the positive inversely symmetric matrix $A$ are slightly changed, the eigenvalues will also change slightly (Saaty 1980). That is, with small changes in the coefficients of the consistent matrix, the maximum eigenvalue $\lambda_{\max}$ will remain close to $n$. To evaluate the measure of consistency, it is necessary to calculate the deviation $\lambda_{\max}$ from the number $n$. In this connection, a coefficient called the consistency index (CI)

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

is introduced. Notice that inequality $\lambda_{\max} \geq n$ is always true.

Consistency index of the randomly generated on a scale from 1 to 9 of an inversely symmetric matrix, is called a random index (RI). By the experimental way described in (Saaty 1980), average RI for matrices of the order from 1 to 15 are generated, Table 2.

The ratio of CI to the average RI for a matrix of the same order is called the consistency ratio (CR). The value of CR such that $CR \leq 0.10$ can be considered acceptable. This approach for determining the consistency of the pairwise comparison matrix is not the only one, see (Cavallo 2019).

To find the weights of the criteria, it is necessary to find an arbitrary eigenvector corresponding to $\lambda_{\max}$. And then, to make the sum of weights equal to one, each component of the vector is divided by the sum of all components.

In case of the consistent matrix, the $i$-th coordinate of the eigenvector coincides with the geometric mean of the $i$-th row. So the weight of the $i$-th criterion can be calculated by the formula:

$$\omega_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}$$

where $a_{ij}, i = 1, \ldots, n, j = 1, \ldots, n$ are components of a consistent matrix. The formula is very simple to calculate. Therefore, in case of small changes in the matrix

| $n$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|-----|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|
| RI  | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 | 1.48 | 1.56 | 1.57 | 1.59 |
coefficients, i.e. when the pairwise comparison matrix is formed, when the matrix consistency is usually violated, but the consistency ratio is within acceptable limits, the criteria weights can be found by formula (2).

### 2.2.7. AHP + Direct ranking method

Using only numbers 1, 2, 3, 4, 5, 6, 7, 8, 9, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9 in the pairwise comparison matrix is not always rational. Due to the limitations of these values, the Saaty method was criticized. For example, if one criterion corresponds to a degree of importance of 4 and another to 3, then we can assume that the first criterion is 4/3 times more important than the second and there is no such number in the Saaty list. Therefore, it is better not to use only the mentioned above numbers in the pairwise comparison matrix. In this case, the degree of importance of criteria in comparison with each other can be evaluated more accurately, it is possible to obtain a consistent pairwise comparison matrix and it is not necessary to calculate the consistency ratio (Zolekar and Bhagat 2015; Kumar et al. 2019).

Let us describe the process of finding criterion weights. Before forming the pairwise comparison matrix, we arrange the criteria $X_1, X_2, \ldots, X_n$, for example, in descending order of importance. Let us denote these criteria $Y_1, Y_2, \ldots, Y_n$, with numerical values of importance $r_1 \geq r_2 \geq \ldots \geq r_n$.

The pairwise comparison matrix is formed as follows: $a_{ij} = \frac{r_i}{r_j}, i = 1, ..n, j = 1, .., n$, that is, the criterion $Y_j$ is more significant than criterion $Y_i$ by $r_i/r_j$ times. We get the following matrix:

$$ A = \begin{pmatrix} 1 & \frac{r_1}{r_2} & \frac{r_1}{r_3} & \ldots & \frac{r_1}{r_n} \\ \frac{r_2}{r_1} & 1 & \frac{r_2}{r_3} & \ldots & \frac{r_2}{r_n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{r_n}{r_1} & \frac{r_n}{r_2} & \frac{r_n}{r_3} & \ldots & 1 \end{pmatrix} $$

Obviously, the matrix $A$ is consistent, since the condition (1) is satisfied. Therefore, we can apply the formula (2) and get the following formula to find the criteria weights.

$$ \omega_i = \frac{\left( \prod_{j=1}^{n} a_{ij} \right)^{1/n}}{\sum_{i=1}^{n} \left( \prod_{j=1}^{n} a_{ij} \right)^{1/n}} \frac{(r_i)^{1/n}}{(r_1 \cdot r_2 \cdot \ldots \cdot r_n)^{1/n}} = \frac{r_i}{r_1 + \ldots + r_n} \quad i = 1,.., n \quad (3) $$

Thus, if we have one expert that we fully trust, it can arrange the criteria and determine the numerical values of the criteria’ importance $r_j, j = 1, \ldots, n$. The weights of the criteria, in this case, are found by formula (3).

If there is no such expert, the group of experts is interviewed and if their opinions are consistent, the weights of the criteria are determined by the direct ranking method. Selecting as the value of the degree of significance of the $j$-th criterion, $r_j$, the sum of evaluations of all the experts according to the $j$-th criterion, $R_j$, that is $r_j = R_j$, it is not difficult to notice that the weights $\omega_i$ found by the formula (3) and the weights $\alpha(j)$ found by the direct ranking method are the same. Therefore, it is not appropriate to apply the Saaty method in the case of group expert assessment.

So, in our case, we will use the direct ranking method. Six experts gave their assessment to each criterion using natural numbers from 1 to 9, is the most significant, 1 is the least significant and the numbers can be repeated (Table 3).

To check the consistency of the experts’ opinions, we calculate Kendall’s $W$ and apply Pearson’s chi-squared test. Since the first expert has given the same assessments to two groups ($l = 2$) of criteria: $X_2, X_6$ and $X_3, X_7$ in Table 3, we apply the formula

$$ W = \frac{12S}{m^2(n^3 - n) - m \sum_{j=1}^{m} T_j}, $$

where

$$ m = 6, \quad n = 8, $$

$$ T_1 = \sum_{i=1}^{2} (t_i^1 - t_j^1) = t_1^1 - t_1 + t_3^1 - t_2 = 2^3 - 2 + 2^3 - 2 = 8 - 2 + 8 - 2 = 12, $$

$$ S = \sum_{j=1}^{8} \left( R_j - \overline{R} \right)^2 = 1403.875 $$

Thus

$$ W = \frac{12 \cdot 1403.875}{36(8^3 - 8) - 6 \cdot 12} = 0.93. $$

We consider the hypotheses $H_0$: the expert opinions are not consistent, with the alternative $H_1$: the expert opinions are consistent. We calculate the actual value

| $X_i$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ |
|------|------|------|------|------|------|------|------|
| expert 1 | 3 | 1 | 2 | 5 | 9 | 1 | 2 | 4 |
| expert 2 | 5 | 2 | 4 | 8 | 9 | 7 | 6 | 3 |
| expert 3 | 2 | 1 | 6 | 9 | 8 | 7 | 4 | 3 |
| expert 4 | 7 | 3 | 1 | 9 | 8 | 6 | 5 | 4 |
| expert 5 | 6 | 5 | 1 | 7 | 9 | 8 | 2 | 3 |
| expert 6 | 6 | 2 | 1 | 8 | 9 | 7 | 4 | 3 |
| $R_j$ | 29 | 14 | 15 | 46 | 52 | 36 | 23 | 20 |

$R = 235$
\[ \chi^2 = m(n - 1) \cdot W = 6 \cdot 7 \cdot 0.93 = 39.06 \]

choose confidence level \( 1 - \alpha = 0.95 \), we have \( n-1 = 7 \) degrees of freedom. By the quantile tables \( \chi^2(7) \), we find \( X_{0.95}^2(7) = 14.067 \), that is \( \chi^2 > X_{0.95}^2 \). Thus, we reject the hypothesis \( H_0 \) with reliability \( 1 - \alpha = 0.95 \) and believe that the experts’ opinions are consistent. In this case, the actually achieved significance level is 0.00000019, that is, the hypothesis \( H_0 \) is rejected with a confidence level 0.9999981.

We calculate weighting coefficients for criteria of evaluation of potential land suitability, ordered by the step of decreasing importance, Table 4.

### 3. Assessment of land suitability for spring wheat cultivation

As a result of GIS layer analysis, spatial boundaries of ESs are established (41 ESs are selected in total) by the selected criteria (see Figure 3). Each ES has a unique number, geometric characteristics in the form of area and perimeter, relief slope and slope exposure, boundary contour coefficient, salinity, soil erosion degree, drainability and others.

The geoinformational analysis of raster and vector layers allowed to make tables of values of eight criteria for each ES. Further categories were defined for the values of each criterion. For each criterion, a set of a categories was formed based on generally accepted classifications and research objectives. For example, for the criterion \( Y_4 \), the slope (in degrees), the following 6 categories were defined: 1) \([0; 1)\); 2) \([1; 3)\); 3) \([3; 5)\); 4) \([5; 7)\); 5) \([7; 9)\); 6) more than 9. The first category is the best.

The numerical characteristic of suitability is the land suitability index, which is calculated for each ES using WLC method (Malczewski and Rinner 2015). WLC is the most commonly used of GIS-MCDA methods. Applying this method to find the suitability indices, we use the weights of criteria \( \omega_j \), \( i = 1, \ldots, n \), (see Table 4) and standardized values \( m(\alpha_j) \) of each criterion \( Y_j \), \( j = 1, \ldots, n \) for each alternative \( A_i \). Thus, the land suitability indices are calculated by the formula \( F(A_i) = \sum_{j=1}^{n} \omega_j m(\alpha_j) \), where

\[ m(\alpha_j) \text{ we find by the following formulas:} \]

\[ m(x) = \frac{x_{\text{max}} - x}{x_{\text{max}} - x_{\text{min}}} \]

\[ m(x) = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \]

\[ m(x) = 0.2 + 0.8 \cdot \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \]

Each criterion has its own standardization formula, see Table 5:

According to FAO, all lands are classified into highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and unsuitable (N) (see Figure 4). The following results are obtained (Table 6, Table 7):

The maximum land suitability index is 0.898, the minimum is 0.58, the interval \([0.58; 0.898)\) is divided into four equal intervals, each of which corresponds to its own suitability class (4 classes in total).

The highly suitable lands are covered by ordinary medium-high-power middle-loam chernozems. Absence of the main limiting factors such as erosion, over wetting and salinity of soils encourages the cultivation of wheat with high yields. Elementary surfaces are characterized by a small contouring of boundaries with contour coefficient less than 2, lie on flat areas with relief slope of less than 1 degree and with groundwater depth of more than 6 m.

The moderately suitable lands are represented by ordinary chernozem of low power, weakly washed, as well as meadow-chernozem medium-thick soils. The main negative factor for obtaining high productivity is water erosion of soils. ESs lie on gentle slopes in the flow

| Table 4. Weights of criteria. |
|-------------------------------|
| **Criterion \( Y_j \), \( i = 1, \ldots, 8 \).** | **Criterion weight, \( \omega_j \), \( i = 1, \ldots, 8 \).** |
| \( Y_1 \) | Erodibility | 0.221 |
| \( Y_2 \) | Capacity of the humus horizon | 0.196 |
| \( Y_3 \) | Salinity | 0.153 |
| \( Y_4 \) | Slope | 0.123 |
| \( Y_5 \) | Drainability | 0.098 |
| \( Y_6 \) | Contouring | 0.085 |
| \( Y_7 \) | Granulometric composition | 0.064 |
| \( Y_8 \) | Slope exposure | 0.060 |
hollows and along the river banks with the relief slope from 2 to 3 degrees, are characterized by higher rugged. Depth of groundwaters in the investigated part of the territory is from 4 to 6 m.

The marginally suitable lands are formed by grey forest solidified medium-power soils. The contouring of the boundaries of elementary surfaces is small and is less than 2, the slope is also small – from 1 to 3 degrees.
However, the close proximity of groundwater to the surface (3–4 m) and the presence of woody vegetation with birch plantations make these lands of marginally suitable for wheat cultivation.

Unsuitable lands cover a significant part of the investigated territory. The soil cover is varied and represented by boggy lowland peat soils, meadow-boggy, meadow saline soils. ESs formed on flat and gently undulating areas with a slope less than 2 degrees, are characterized by average, strong and very strong contouring of boundaries. Limiting factors for the use of these lands for wheat are overwetting of soils (close groundwater occurrence to the surface – less than 1 m), as well as salinity of the soil.

4. Conclusion

In order to implement multi-criteria analysis based on GIS, it is necessary to create a spatial database of high-

| Table 5. Standardization formulas. | Standardization formula, converts the criterion value into a scale [0; 1] (the closer to 1, the better) |
|-------------------------------------|--------------------------------------------------------------------------------------------------|
| Criterion \( Y_j \)                  |                                                                                                   |
| 1. erodibility (5 categories, lower-the-better) | \( (I), x_{\text{max}}=5, x_{\text{min}}=1 \)                                                   |
| 2. capacity of the humus horizon (4 categories, higher-the-better) | \( (I), x_{\text{max}}=4, x_{\text{min}}=1 \)                                                   |
| 3. salinity (4 categories, lower-the-better) | \( (I), x_{\text{max}}=4, x_{\text{min}}=1 \)                                                   |
| 4. slope (6 categories, lower-the-better) | \( (I), x_{\text{max}}=6, x_{\text{min}}=1 \)                                                   |
| 5. drainability (5 categories, lower-the-better) | \( (I), x_{\text{max}}=5, x_{\text{min}}=1 \)                                                   |
| 6. contouring (4 categories, lower-the-better) | \( (I), x_{\text{max}}=4, x_{\text{min}}=1 \)                                                   |
| 7. granulometric composition (4 categories, lower-the-better) | \( (I), x_{\text{max}}=4, x_{\text{min}}=1 \)                                                   |
| 8. slope exposure (5 categories, higher-the-better) | \( (III), x_{\text{max}}=5, x_{\text{min}}=1 \)                                                   |

![Figure 4. Land suitability map of wheat.](image)
resolution geodata using geo-information technologies and remote sensing of the Earth. This work was carried out at the test plot of land-use of CJSC Mirny, Kochenevsky District, Novosibirsk Region. As the main essences of the cartographic and attributive components of the geodatabase were provided with a large-scale orthophotoplane (M 1:1000), digital elevation model (DEM, 0.10 cm spatial resolution), forest belts, land plots, wood vegetation, shrubs, ponds, soil contours, roads. High-resolution orthophotoplane, DEM and DLSLM was created. Spatial boundaries of ESs, which are the smallest taxonomic units of a land suitability assessment and are characterized by the values of criteria selected for analysis, are defined.

In order to make a multi-criterion analysis, eight main criteria related to relief and soil were identified. The analysis of these criteria allows us to make a conclusion about ES suitability for the placement of spring wheat crops. The group of experts evaluated each criterion, the expert opinions were checked for consistency by statistical methods. Since the criteria have a different degree of significance, the weights of the criteria were determined. Two methods of obtaining criterion weights have been analysed: AHP and the direct ranking method. It was shown that for a certain construction of a pairwise comparison matrix, namely, a matrix that is consistent by definition, the weights of the criteria in both methods will be the same. In order to apply the weighted linear combination, besides the criteria weights, it is necessary to convert the values of each criterion on each elementary land plot to a scale [0; 1], i.e. to make standardization. Before the standardization procedure, categories were specified for each criterion and all the values of the criteria were distributed in these categories. Then, the values were standardized so that the closer the value is to one, the better. Standardization is necessary because all criteria have different units of measurement and not all criteria have continuous numerical values.

Formulas for standardization are given for each criterion. The standardization procedure is analogous to the application of membership functions in the theory of fuzzy sets (Zhang et al. 2015). In our case, the standardization functions are piece-linear, monotonic. There are no trapezoidal standardization functions for the criteria under consideration since the criteria are such that the values are either higher-the-better or vice versa. That is, there are no such criteria as temperature, for example, where there is a minimum, maximum value and some range of optimal temperature within the interval between the minimum and maximum.

The FAO classification was used to assess the suitability of Western Siberian forest-steppe lands for wheat cultivation. Belonging to a particular suitability class according to FAO was determined using the land suitability index. GIS-MCDA method weighted linear combination was used to calculate the land suitability index of selected land plots.

As a result of the research, it was found out that on the territory of the test plot of CJSC ‘Mirny’, with the area of 1071.56 ha, unsuitable lands for spring wheat cultivation amount to 367.38 ha (34%) and the highly suitable – 596.4 ha (56%). The most suitable lands are covered by ordinary Chernozems and are characterized by the absence of the main limiting factors – erosion, overwetting and salinity of soils. Therefore, spring wheat can be cultivated on these lands with high yields. Unsuitable lands are covered by boggy lowland peat soils, meadow-boggy and meadow saline soils. The limiting factors for using these lands for spring wheat are overwetting of soils and their salinity.

**Disclosure statement**

No, potential conflict of interest was reported by the authors.
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