Evaluation of Current State of Agricultural Land Using Problem-Oriented Fuzzy Indicators in GIS Environment

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Abstract. Current state of agricultural lands is defined under influence of processes in soil, plants and atmosphere and is described by observation data, complicated models and subjective opinion of experts. Problem-oriented indicators summarize this information in useful form for decision of the same specific problems. In this paper, three groups of problem-oriented indicators are described. The first group is devoted to evaluate agricultural lands with winter crops. Second group of indicators oriented for evaluation of soil disturbance. The third group of indicators oriented for evaluation of the effectiveness of soil amendments. For illustration of the methodology, a small computation was made and outputs are integrated in Geographic Information System.

Keywords: Problem-oriented indicators · Soil disturbance · Damage of winter crops · Fuzzy and crisp models · Spatial extension of fuzzy set theory

1 Introduction

In a general sense, indicators are a subset of the many possible attributes that could be used to quantify the condition of a particular landscape or ecosystem. They can be derived from biophysical, economic, social, management and institutional attributes, and from a range of measurement types [1]. Traditionally, results from physical and statistical analysis of agricultural field have been used as indicators [2, 3].

In many cases, indicators are developed for decision of any problem. For example, recently several indicators have been developed to address a variety of questions and problems related to land evaluation [4, 5], for managing precision agriculture [6, 7], for evaluation of yield maps [8, 9], evaluation of agricultural land suitability [10, 11],

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assessment of soil quality [12, 13], evaluation of resources of agricultural lands [14, 15], zoning of an agricultural fields [16, 17] and other land use planning [18, 19].

Such indicators can be referred to as problem-oriented indicators. Problem-oriented indicators are increasingly being used for diagnostic of current state of agricultural lands and for improvement of decision support processes. Indicators can be valuable tools for evaluation and decision making because they synthesize information and thus can help in the understanding of complex systems [20].

Problem-oriented indicators are the core of the problem-oriented approach [21]. In this approach, current state of agricultural lands is defined by the specific conditions of soil processes, plants, and atmosphere. The conditions are described by observational data, complicated models, and subjective opinion of experts [22]. The problem-oriented indicators summarize this information into a useful form that can be used for decisions regarding these specific problems.

Among the many potential indicators we will focus on three groups.

The first group is devoted to the evaluation of agricultural lands with winter crops. It is well known that damage of winter crops is primarily related to three main factors: (a) influence of adverse agrometeorological conditions, (b) soil temperature in the root area, and (c) winter crop response from negative environmental conditions. The interaction of these factors is very complicated. Therefore, the use of indicators which described damage of winter crops is useful for management of agricultural lands in winter.

The second group of indicators to be considered is those used for evaluation of soil disturbance. Assessment of soil disturbance is very important for making decisions on agricultural and ecological management.

The third group of indicators to be considered is those used for evaluation of the effectiveness of soil amendments. Soil amendments have been shown to be useful for improving soil condition, but it is often difficult to make management decisions as to their usefulness. In Europe as a whole, nearly 60 % of agricultural land has a tendency towards acidification. However, most crops prefer near neutral soil conditions. Traditionally, lime has been added in order to improve acid soils conditions. But precipitation is continual in these regions and after some years the soil conditions becomes acidic again. Therefore, assessment of the effects of additions of liming compounds on soil structure and strength using indicators has a practical interest.

In this paper, three groups of problem-oriented indicators are described. For illustration of the methodology, a small computation was made and outputs are integrated into a Geographic Information System (GIS).

2 Evaluation of Damage of Winter Crops by Frost

The monitoring of frost injury is the most important aspect of the monitoring of agricultural fields for winter crops. Evaluations of frost damage of winter crops has been discussed in many publications [23, 24].

Damage of winter crops is related to three main factors: (a) influence of the adverse agrometeorological conditions, (b) soil temperature in the root area, and (c) winter crops response to the adverse agrometeorological conditions.

Many studies of heat transfer in soil have been performed. Several researchers have observed soil temperature during the winter period and have described two processes which characterize this period: soil freezing and soil thawing [25]. Soil temperature of the root area (at 2 cm depth) is dependent on the depth of the boundary between the frozen and melted top soil layers and, the thickness of the snow cover. Model of soil temperature in the root area has been developed in framework of the general theory of heat transfer in soil [24].

2.1 Modelling Winter Crops Response on the Adverse Agrometeorological Conditions

It is well known [23] that the winter crop resistance to frost is dependent on the kind of crop, and planting density (the number of stems) determines the amount of thermal damage sustained to the winter crop. Also, frost injury is related to the crop's growth stage. For example, if at the end of autumn the winter crop's development is normal, the resistance to frost will be strong. If the winter crop is underdeveloped or outgrowing, then the resistance to frost will be decreased.

The base postulates for developing Indicator of Frost Damage (IFD) are formulated as follows:

(1) IFD is defined as a number in the range from 0 to 1, and modeled by an appropriate membership function.
(2) The choice of a membership function is somewhat arbitrary and should mirror an objective of expert opinion.

The critical temperatures (T_{root}) can be defined as the soil temperature at 2 cm depth at which the winter crop will be destroyed. The Indicator of Frost Damage (IFD) can be described as follows (parameters n_1 and n_2 are defined by Table 1):

$$IDF = \begin{cases} 0, & T_{root} > n_1, \\ f(T_{root}), & n_2 \le T_{root} \le n_1, \\ 1, & T_{root} < n_2 \end{cases} \quad (1)$$

It can be observed if IFD is equal to 1, then there is a maximum impact of frost. If IFD is equal to 0, then the damage to winter crops is negligible. The $f(T_{root})$ in most cases is a linear function.

2.2 Example 1

In this example we used agricultural area located near Saint-Petersburg, Russia, which contains several homogeneous plots. Spatial distribution of winter crops are shown in

Fig. 1. In this example to illustrate this approach, the IFD is modeled by an increasing piecewise-linear membership function. Results of computations are shown in Figs. 2 and 3 for two variants ($T_{root} = -15$ °C and $T_{root} = -20$ °C).

Table 1. Values of parameters n_1 and n_2

Winter crops	n_1, °C	n_2, °C
Barley:		
• Underdeveloped crop	−7	−12
• Normal crop	−14.8	−19.2
• Outgrowing crop	−7	−13
Rye:		
• Underdeveloped crop	−11	−22
• Normal crop	−14	−25
• Outgrowing crop	−11	−22
Wheat with mean frost resistance:		
• Underdeveloped crop	−11	−17
• Normal crop	−14	−19.4
• Outgrowing crop	−10	−15

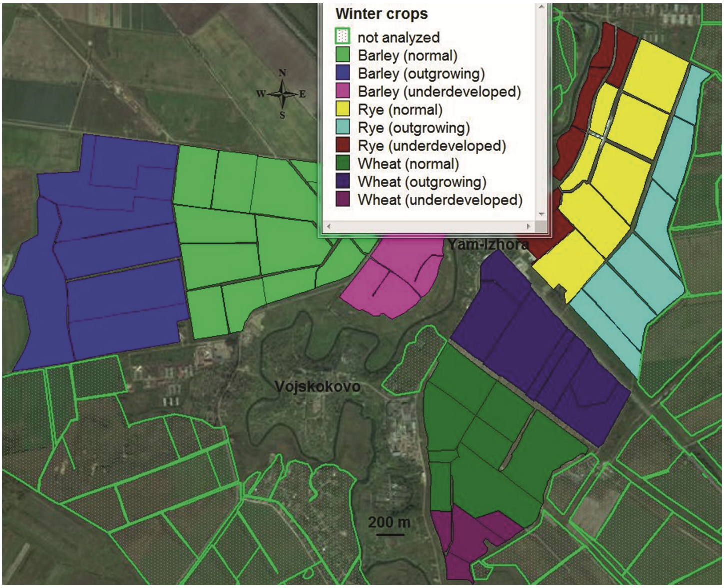

Fig. 1. Allocation of winter crops (Color figure online)

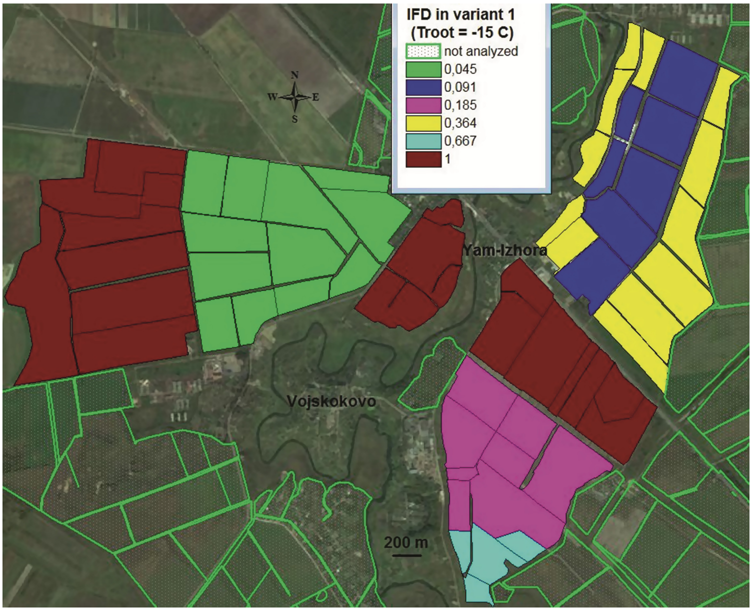

Fig. 2. IFD in variant 1 ($T_{root} = -15$ °C) (Color figure online)

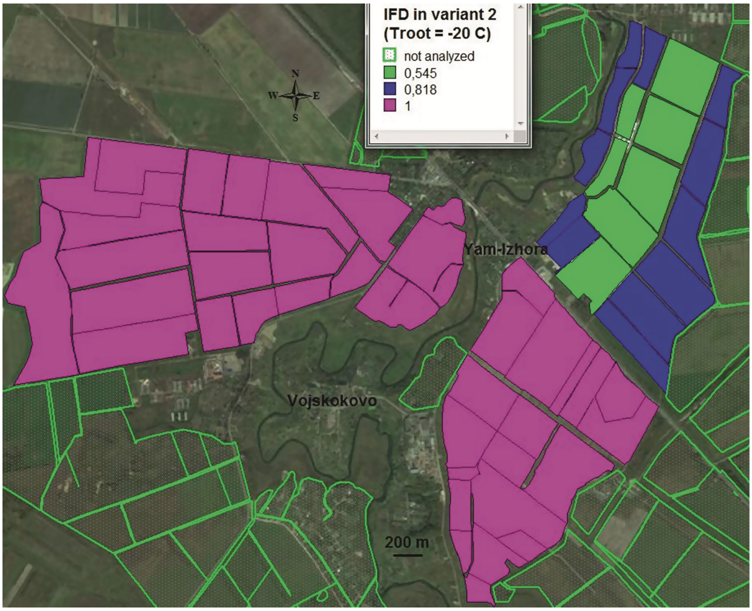

Fig. 3. IFD in variant 2 ($T_{root} = -20$ °C) (Color figure online)

3 Evaluation of Soil Amendments

Soil amendments have been shown to be useful for improving soil condition, but it is often difficult to make management decisions as to their usefulness. Recently a tool based on fuzzy indicator model was developed [26, 27]. The effectiveness of soil amendments in the frame of work of this tool can be evaluated by two indicators: Impact Factor Simple (IFS) and Impact Factor Complex (IFC). Using IFS, an estimate of the effectiveness of soil amendments can be determined when only one experimental soil parameter is available. Using IFC, an estimation of soil amendment effectiveness can be calculated based on information about several soil parameters. This methodology was utilized in two case-studies. In the first, evaluation of the effectiveness of using polyacrylamide application as an amendment to reduce subsoil compaction was evaluated [28]. In the second, the evaluation of the organic material “Fluff” as a soil amendment for establishing native prairie grasses was evaluated [29].

IFS is defined as follows [28]:

$$IFS = (P_{max} - P)/(P_{max} - P_{min}), \quad P_{min} \leq P \leq P_{max}, \tag{2}$$

where P is the soil parameter under consideration (current value), P_{min} is the minimal value of the soil amendment under consideration, and P_{max} is the maximal value for the soil parameter under consideration. In this article the tool [26] is applied for evaluation of the residual effects of additions of calcium compounds on soil structure and strength [30, 31].

3.1 Example 2

In Europe as a whole, nearly 60 % of the agricultural land has a tendency towards acidification [29]. Acidification is a natural process for regions with humid climatic conditions where the precipitation exceeds the evapotranspiration. However, most crops prefer near neutral soil conditions. Traditionally, lime has been added in order to improve soil acidity. But, in these regions the continuous precipitation will result in the return to acidic soil conditions after some years the calcium is washed out.

For a better understanding for agriculture, the effects of the additions of calcium compounds, such as lime and gypsum, on soil strength and structure have been of direct interest [30], [32]. Tensile strength is a particularly useful measure of soil strength because it is sensitive to the micro-structural condition of the soil [29]. The goal of the present example is to illustrate the application of IFS for assessment of the effects of the additions of calcium compounds on soil structure and strength. As the starting point, known models are utilized [29]. The linear regression equations describing the relationships are:

$$S = n_1 + n_2\, Ca^{2+} + n_3\, w, \tag{3}$$

$$R = m_1 + m_2\, Ca^{2+} + m_3\, w, \tag{4}$$

where S is tensile strength (kPa), R is fracture surface roughness of soil clods (mm), n_i and m_i, i = 1, 2, 3 are empirical coefficients (Table 2), Ca^{2+} is the amount of calcium applied (kg kg^{-1}), and w is the soil water content (kg kg^{-1}). The equations have been obtained in the 0–4 * 10^{-3} kg kg^{-1} range for Ca^{2+} and 0,1–0,22 kg kg^{-1} range for w.

Table 2. Empirical coefficients n_i and m_i, in Eqs. (3) and (4)

In formula for tensile strength		In formula for fracture surface roughness of soil clods	
n_1	9.5	m_1	0.21
n_2	−324	m_2	−8.4
n_3	−18	m_3	0.26

Table 3. Predicted values of tensile strength (S) and IFS on S

Amounts of calcium, kg kg^{-1}	S, kPa	IFS on S
0	6.8	0
0.001	6.476	0.249231
0.002	6.152	0.498462
0.004	5.504	1

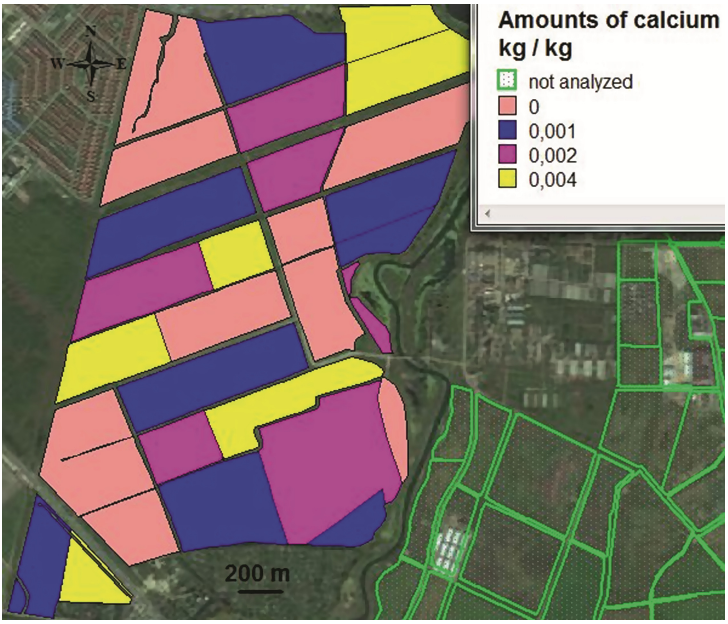

Fig. 4. Distribution of amounts of calcium (Color figure online)

The model describes situations when no tillage occurs (e.g., under long-term pastures) and under natural rainfall conditions. Also, the linear regression equations above give the residual effects calcium compound additions on structurally-degraded soil 6–7 years after the application of the calcium compounds [33]. Taking into account that range for Ca^{2+} is 0–4 * 10^{-3} kg kg^{-1} we calculated predicted values of tensile strength S and IFS on S (Table 3).

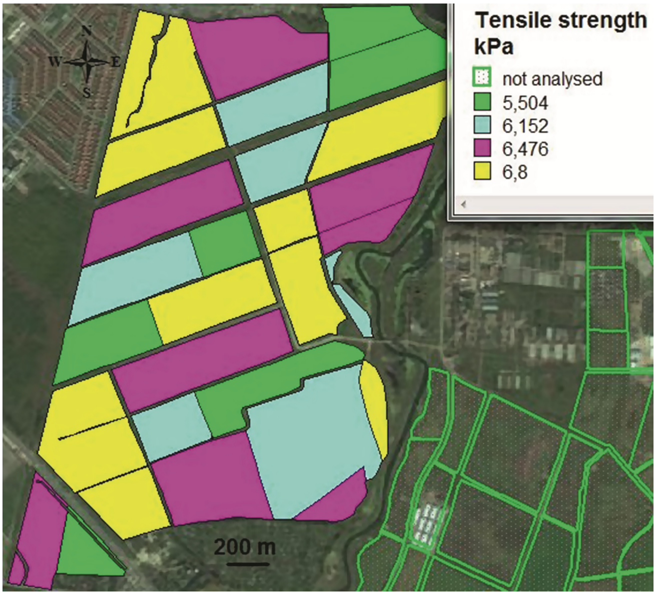

Fig. 5. Distribution of S (Color figure online)

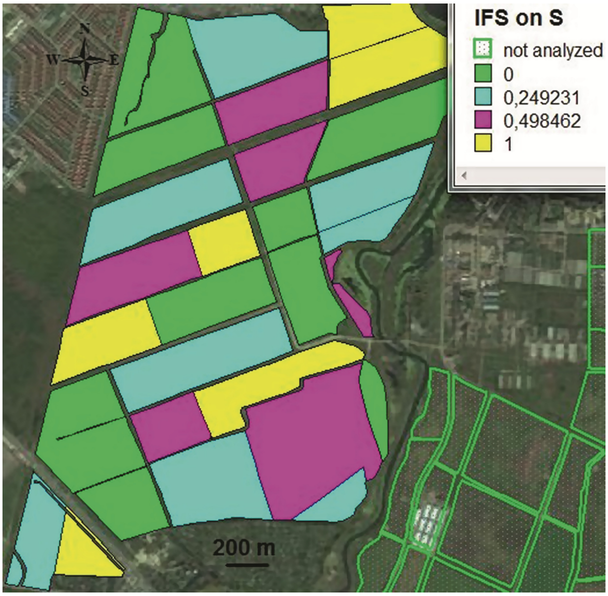

Fig. 6. Distribution of IFS on S (Color figure online)

For this example, we utilized the agricultural territory located near the Saint-Petersburg, Russia, which we used early. It was assumed that the amount of calcium compounds were distributed as shows in Table 3. Distribution of amounts of calcium and S are shown in Figs. 4 and 5. Distribution of IFS on S is given in Fig. 6.

4 Evaluation of Soil Disturbance

Soil disturbance is a great problem and the evaluation of soil disturbance is very important for making decisions on agricultural and ecological management. Small levels of soil disturbance can result in soil surface erosion and soil mass movement. This commonly leads to loss of surface organic matter and a reduction in soil quality. Recently, a new method for potentially evaluating soil disturbance is described [34].

With this method, the usage of two indicators called "Disturbance Factor Simple (DFS)" and "Disturbance Factor Complex (DFC)" were suggested. The DFS is defined as a number in the range from 0 to 1, and modeled by an appropriate membership function. It reflects measured soil parameters which are affected by soil disturbance. In [35], DFS is modeled by an increasing piecewise-linear membership function and can be presented as follows:

$$\mathrm{DFS} = \begin{cases} 0,\ \text{if } \mathrm{Y} = 0 \\ \mathrm{Y},\ \text{if } 0 < \mathrm{Y} < 1 \\ 1,\ \text{if } \mathrm{Y} = 1 \end{cases} \tag{5}$$

$$y = (P_n - P_d)/(P_{max} - P_{min}),\quad Y = |y| \tag{6}$$

$$P_{max} = \max\left(P_{max,\,n}, P_{max,\,d}\right) \tag{7}$$

$$P_{min} = \min\left(P_{min,\,n}, P_{min,\,d}\right) \tag{8}$$

where P is a soil parameter, P_n is the soil parameter on site in natural conditions (no disturbance) ($P_{min,n} \leq P_n \leq P_{max,n}$), P_d is the soil parameter on site with disturbance ($P_{min,d} \leq P_d \leq P_{max,d}$), P_{min} is the minimal value, P_{max} is the maximal value, and Y is an absolute value (modulus) of y.

The DFC is calculated by combining individual DFS components using fuzzy aggregation algorithms. Using DFC it is possible to assess the combined effect of several DFS to improve the sensitivity of measuring potential soil disturbance impacts.

4.1 Example 3

On the agricultural territory located near Saint-Petersburg, Russia, which we utilized in example 1, there are several fields where processes of soil disturbance are currently occurring. For spatial planning, it is necessary to estimate the level of soil disturbance which has occurred in comparison with the current state of soil on neighboring fields. In this example, weighted coefficients of the significance of soil parameters were

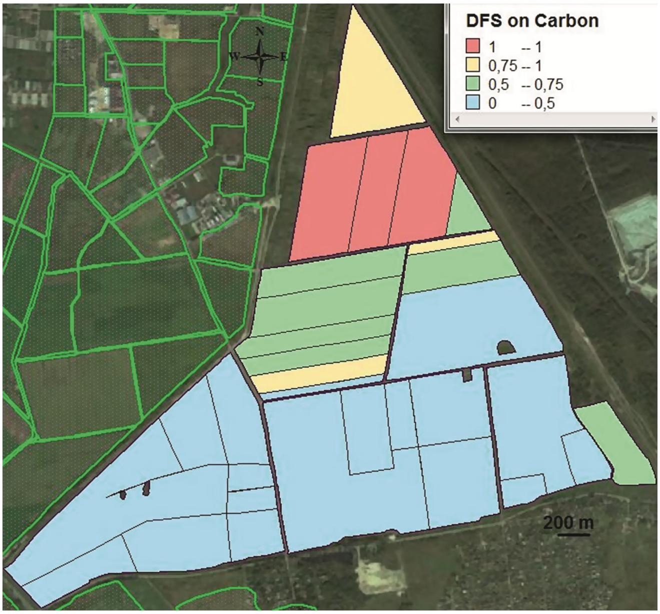

Fig. 7. Allocation of DFS on Carbon (Color figure online)

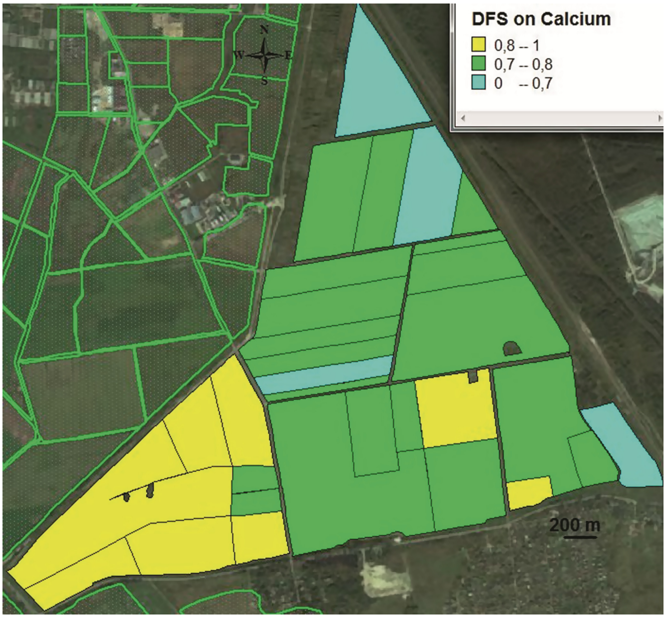

Fig. 8. Allocation of DFS on Calcium (Color figure online)

assigned as equally important. Results of the computation of DFS and DFC in topsoil are shown in Figs. 7, 8 and 9. Here only fields with soil disturbance were analyzed.

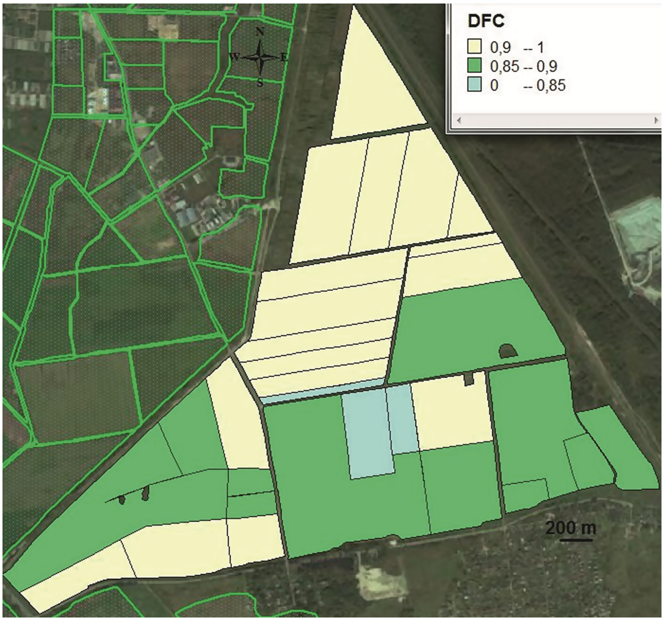

Fig. 9. Allocation of DFC (Color figure online)

5 Conclusions

Current state of agricultural lands was defined under influence of soil processes, plants, and atmosphere and was described by observational data, complicated models and subjective expert opinions. The problem-oriented indicators summarized this information into a useful form for use in decisions regarding these same specific problems.

In this paper, three groups of problem-oriented indicators are described. The first group was devoted to evaluation of agricultural lands growing winter crops. The second group of indicators evaluated soil disturbance. The third group of indicators evaluated of the effectiveness of soil amendments. For illustration of the methodology, a small computation was made and outputs were integrated into GIS.

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