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RESEARCH ARTICLE

Identification of fertility zones and assessment of potential crop yield based on biological farming approaches

Natalia V. Ovcharova[1], Marina M. Silantieva[1], Vladimir I. Belyaev[2], Yuri A. Gulyanov[3], Lyudmila V. Sokolova[1], Tatiana G. Plutalova[4], Irina Yu. Botvich[5], Dmitriy V. Emelyanov[5], Nikolai P. Belov[6]

1 *Altai State University, 61 Lenin Ave., Barnaul, 656049, Russia*
2 *Altai State Agrarian University, Barnaul, 98 Krasnoarmeisky Ave., 656049, Russia*
3 *Orenburg Federal Research Center, Institute of Steppe of the Ural Branch of the Russian Academy of Sciences, Orenburg, 11 Pionerskaya St., 460000, Russia*
4 *Institute for Water and Environmental Problems of the Siberian Branch of the Russian Academy of Sciences, Barnaul, 1 Molodezhnaya St., 656038, Russia*
5 *Institute of Biophysics SB RAS 50-50 Akademgorodok, Krasnoyarsk, 660036, Russia*
6 *SPK Znamya Rodiny (Agricultural Production Cooperative), Altai Krai, Pospelikhinsky district, Kalmytskie Mysy, 8 Traktovaya St., 659715, Russia*

Corresponding author: Natalia V. Ovcharova (ovcharova_n_w@mail.ru)

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Abstract

The biopotential productivity of agricultural land, along with the preservation of the biological diversity of adjacent landscapes through the development and implementation of high-tech agricultural technologies, is of critical concern in the current climatic changes and urbanization. The article reports the results of an integrated approach to the development of task maps for differentiated seeding and mineral fertilization using various tillage techniques (conventional subsurface tillage and no-till) in the experimental fields of two farms in the Altai Krai. The farms are located in the Aleiskaya soil and climate zone. The soils in the experimental fields showed a very low nitrate nitrogen content, which did not exceed 3.0 mg/kg of soil in the upper (0–10 cm) layer and 2.7 mg/kg of soil in the 10–20 cm layer. We revealed that one of the main indicators that affects soil fertility is the spatial differentiation of the humus content of humus and the main nutrients. Soil moisture was found to vary at different soil depths (11.4–25.3%), indicating a significant effect of soil fertility grades and autumn tillage techniques on moisture accumulation and distribution at different soil depths in spring, and consequently on the vegetation soil moisture regime and crop yield.

Keywords
Agrocenoses, Altai Krai, bioclimatic potential, NDVI, MSAVI2, precision agriculture

Introduction

Currently, differentiated mineral fertilization is one of the most relevant economic and environmental issues in precision agriculture. This crop cultivation technology can significantly increase the efficiency of the agroclimatic potential of areas with different levels of natural fertility (Schellberg 2008; Yakushev et al. 2009; Afanasiev 2010; Belenkov et al. 2011).

The concept of precision agriculture based on the principles of biologization treats a field as a set of field zones heterogeneous in their physical, chemical and biological characteristics; it differentiates the norms of the technological impact for their elimination, including spatial variation in mineral fertilizer rates (Chekmarev and Lukmanov 2011; Matveenko 2012; Lyubchich et al. 2012; Lobkov and Plygun 2012; Kustarnikov et al. 2013; Belenkov et al. 2013; Eremin and Kibuk 2017). Theoretical principles of the biological farming approach have long been formulated. However, within this farm management system, they should be implemented with regard to numerous factors, including climatic conditions, a technological level of agriculture and crop rotation practices. In essence, biologized agriculture aims to introduce and adapt energy-efficient and environmentally friendly technologies. Biologized agriculture employs technologies such as precision seeding, fertilization, and harvesting. Landscape farming techniques, high-precision methods (precision agriculture), are of relevance in this area (Ovcharova et al. 2022). Therefore, the development and implementation of innovative steppe farming technologies (differentiated fertilizer and seed rates) to ensure biopotential productivity, along with the preservation and restoration of landscape and biological diversity, is of current relevance both for the Altai Krai and for the country in general.

The purpose of the study was to develop algorithms and methods to identify fertility zones and to map the potential yield of field agrocenoses in the forest steppe of the Altai Krai.

Materials and methods

The study was carried out on farms in the Aleisky and Pospelikhinsky districts, Altai Krai, Russian Federation (Fig. 1). Each farm was allocated two fields with an area of 100 hectares each. The crops studied were sunflower and corn. Table 1 presents the selected zones with different levels of natural fertility for vegetation observations and options for fertilizer and seed rates.

In SPK Znamya Rodiny (Limited Liability Company), the technologies to cultivate sunflowers and corn in the experimental fields were as follows. The predecessors of the cultivated crops were spring wheat and mustard, respectively. Autumn tillage was not carried out. Early spring harrowing was performed. The LG-5462 and Regen hybrids were seeded using an EDX 12000 TS sawder on May 16 and 22. During the growing season (20 June and 12 June), the crops were chemically treated with Global (1.2l/ha) and Oktava (1.0l/ha), respectively.

Table 1. Differentiated seeding and fertilization for sunflower and corn crops

Zone	SPK Znamya Rodiny (Limited Liability Company)		OOO Zolotaya Osen (Agricultural Production Cooperative)
	Seed rate, thousand. pcs/ha	Fertilizer rate (diammofoska 10:26:26), kg/ha /(KAS-32), kg/ha	Seed rate, thousand. pcs/ha
		Crop – sunflower for grain	
I	50	70/112	55
II	40	50/112	45
III	30	30/112	35
		Crop – corn for silage	
I	70	70/112	60
II	60	50/112	50
III	50	30/112	40

In OOO Zolotaya Osen (Agricultural Production Cooperative), the predecessors of the cultivated crops (sunflower and corn) were oats and spring wheat, respectively. In autumn, KPSh and KPG subsurface tillers were used to perform subsurface tillage at depths of 15–17 and 25–27 cm, respectively. The Pioner LE 10 and KWS Korifey hybrids were sown using a Horsch Maestro seeder on May 10 and 19. During the growing season (June 23 and 27), the interrow cultivation of crops was carried out using a KRM-6 cultivator. On 7 July, sunflower crops were chemically treated with a tank mixture (tribenuron-methyl (50 g/ha) + cletodym (250 g/ha) + haloxyfop (250 g/ha) + alpha-cypermethrin (50 g/ha)), and on 21 July, crops were treated with alpha-cypermethrin (50 g/ha). Corn crops were treated with nicosulforon (80g/ha) + florasulam (200g/ha).

The field coordinates are as follows:

OOO Zolotaya Osen (Limited Liability Company) (Fig. 1 (1))
52°26'39.75" N, 82°39'40.90" E (field no. 14).

52°28'54.22" N, 82°34'29.00" E (field no. 47).
SPK Znamya Rodiny (Agricultural Production Cooperative) (Fig. 1 (2))
51°55'30.02" N, 82°15'49.39" E (field no. 7.1).
51°55'43.40" N, 82°13'22.60" E (field no. 6.4).

Electronic maps of differentiated seeding and fertilization were developed based on the agrochemical survey of fields and the analysis of long-term data on the yield of cultivated crops (Ovcharova et al. 2023). Agrochemical analysis of soil was performed by an accredited laboratory (FSBI CAS Altaisky) for soil samples taken prior to spring farm work. The soil was sampled at a given point with a hand auger from the upper (0–20 cm) horizon. Soil analysis determined the following indicators: nitrate nitrogen content, mass fraction of mobile phosphorus and potassium compounds, and organic matter content.

Figure 1. Location of Altai Krai and OOO Zolotaya Osen (Limited Liability Company) (1), SPK Znamya Rodiny (Agricultural Production Cooperative) (2) on the map of Russia.

The Savinov method, which determines the number of aggregates of different sizes by dry sieving, was used to assess the structural and aggregate composition of soil (Vadyunina and Korchaina 1986). An average sample of 0.5–2.5 kg was taken from a sample of undisturbed air-dry soil (cleaned from stones, gravel, roots, and other inclusions, if any) and sieved through a set of sieves with a hole diameter of 10, 7, 5, 3, 2, 1, 0.5, and 0.25 mm. Each fraction of aggregates was prepared separately, weighed, and its percentage of the initial sample mass was calculated. The structural state of the soil was considered excellent if the content of 0.25 to 10.0 mm aggregates exceeded 80% of the mass of absolutely dry soil. The structural state of the soil was evaluated as good if the content of these aggregates was 60-80%, satisfactory for 40–60% and unsatisfactory for 20–40%; soil was considered structureless if the content of the aggregates was less than 20% (Table 2).

Table 2. Agroecological evaluation of the the structural state of soil

The content of 0.25 to 10 mm aggregates, % of air-dry soil mass		Structural state of soil
Dry sieving	**Wet sieving**	
more than 80	more than 70	Excellent
60–80	55–70	Good
40–60	40–55	Satisfactory
20–40	20–40	Unsatisfactory
less than 20	less than 20	Structureless

The structural coefficient was found by the formula:

$$K_{str} = \frac{A}{B},$$

where K_{str} is the structural coefficient; A is the sum of aggregates ranging from 0.25 to 10 mm in size, %; B is the sum of aggregates <0.25 mm and lumps >10 mm, %.

The aggregate state of the soil was evaluated as excellent if the value of the structural coefficient exceeded 1.5, good if the value ranged from 1.5 to 0.7, and unsatisfactory if the value was less than 0.7. The stability was determined using N.N. Nikolsky method. Five aggregates from each fraction of aggregates ranging from 1 to 5 mm in size, obtained by structural analysis, were placed in gradually filled with distilled water 2 cm above the aggregate level. After 20 min, the number of aggregates that did not disintegrate under slow and careful movement was counted. The content of water-stable aggregates in each fraction was determined by the formula:

$$A = Bx100/a,$$

where A is the content of water-stable aggregates in a given fraction (%), a is the number of aggregates analyzed (pcs), and B is the number of non-disintigrated aggregates (pcs).

The soil structure was considered water stable if the average water stability of the aggregates of each fraction ranging from 1 to 5 mm in size exceeded 50%, medium water stable for the average water stability of 20 to 50%, and water unstable for the average water stability less than 20%. Soil moisture before planting crops at a 10-cm interval in layers of up to one meter was evaluated using the volumetric method using the HH-2 moisture meter, and the total moisture reserves in the meter layer were estimated. The vegetation state of field crops was evaluated based on the integral value of NDVI (normalized difference vegetation index) determined during the growing season (May–August), recognized by many researchers (Pisman et al. 2023) as an indicator highly correlated with crop yield (Shevyrnogov et al. 2021).

The NDVI vegetation index and the soil moisture index S2WI for the farm located in the Aleisky district were calculated based on data from the Sentinel-2 satellite with a spatial resolution of 10 and 20 m. For the farm in the Pospelikhinsky district, NDWI was calculated from images obtained from Landsat 8 OLI.

NDVI was calculated using the values of the NIR range at 842 nm (8 channels – b8) and the red range at 665 nm (4 channels – b4) using the formula:

$$NDVI = \frac{b8 - b4}{b8 + b4}$$

The moisture index S2WI (Vaudour et al. 2019) based on three bands of 842 nm (channel 8 – b8), 1610 nm (channel 11 – b11) and 2190 nm (channel 12 – b12) was calculated using the formula:

$$S2WI = \frac{b8 - b11 - b12}{b8 + b11 + b12}$$

Digital terrain models of the fields were built using SRTM data (https://earthexplorer.usgs.gov/) with a spatial resolution of 30 m.

MSAVI2, ARVI, and NDWI were calculated using the following formulas:

MSAVI2 (Modified Soil Adjusted Vegetation Index) was derived from the equation:

$$\text{MSAVI2} = \frac{2 * b5 + 1 - \sqrt{(2 * b5 + 1)2 - 8 * (b5 - b4)}}{2}$$

ARVI (Atmospherically Resistant Vegetation Index) was derived from the equation:

$$\text{ARVI} = \frac{b5 - (b4 - 0.5 * (b4 - b2)}{b5 + (b4 - 0.5 * (b4 - b2)}$$

NDWI (normalized difference water index) is a measure of liquid water molecules in vegetation canopies that interact with incoming solar radiation. NDWI is obtained by the following equation:

$$\text{NDWI} = \frac{b3 - b5}{b3 + b5}$$

The ArcGIS and QGIS software packages were used as the main tools to process cartographic material, visualize tasks and operation schemes, and agrochemical survey data, and study field characteristics (reliefs, slopes).

Result

Different fertility zones were identified in the fields studied in the Aleisky district based on archival surveys. The soil and vegetation spectral reflectance data obtained in 2020, when corn was planted in this field, were used as the basis for assessing intra-field heterogeneity in corn field No. 47. To assess intra-field heterogeneity in sunflower field No. 14, 2022 spectral data were used, since the Sentinel-2 survey was not performed in the period of previous sunflower growing in the same field (2011). In the first stage, the field relief was assessed. The steepness of the slopes, their exposure, and the watercourses were calculated. The data on slope steepness showed prevalence of slopes up to 3°. Significant intra-field heterogeneity was found to be due to a complex system of waterways. This results in the formation of zones with a higher and lower moisture content. The S2WI moisture index to identify zones with different levels of soil moisture, which was used to assess the level of moisture in the experimental fields, showed that the values observed on 27 May 2020 and 27 May 2022 were similar, indicating a temporary prolongation of zones with high and low moisture content.

The data obtained were used to build task maps for differentiated corn and sunflower. The algorithm for constructing task maps to differentiate corn seed rates based on satellite data includes the following steps.

1. Evaluation of field relief characteristics (SRTM), calculation of slope steepness and exposure, calculation of watercourses;
2. Calculation of the spatial distribution of S2WI values in the study field in the spring (Figs 2–3);
3. Calculation of the spatial distribution of the NDVI values by areas of the previous growing season in this field. Calculation of the integral value for the growing season (May – August) (Fig. 4);
4. Comprehensive analysis of the field inhomogeneity characteristics, determination of the intervals of values with respect to different fertility and moisture levels;
5. Decision tree classification based on integral values of NDVI and S2WI, identification of fertility zones of 3 grades with respect to the moisture level:

Grade 1 – Increased fertility.

Grade 2 – normal (moderate) fertility.

Grade 3 – decreased fertility.

6. Vectorization of the data obtained, export in kml and kmz formats.

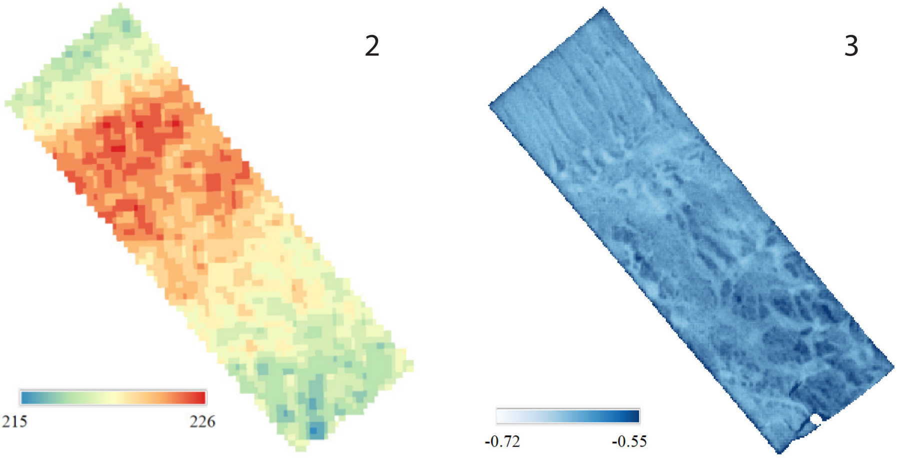
The algorithm for constructing task maps to differentiate sunflower seed rates based on satellite data includes the following steps:

1. Evaluation of field relief characteristics (SRTM), calculation of slope steepness and exposure, calculation of watercourses;
2. Calculation of the spatial distribution of the NDVI values in the study field in the previous growing season (2022), calculation of the integral value for the growing season (May to August) (Figs 5–6);

3. Comprehensive analysis of the features of the intra-field heterogeneity, determination of the intervals of values corresponding to different fertility levels;
4. Decision tree classification based on the NDVI integral values, identification of fertility zones of 3 grades:

Grade 1 – Increased fertility.
Grade 2 – normal (moderate) fertility.
Grade 3 – decreased fertility.

5. Vectorization of data obtained, export in kml and kmz formats.



Figures 2–3. 2 – Digital model of the relief in field No. 47. **3** – Map of the spatial distribution of the S2WI values in field No. 47.

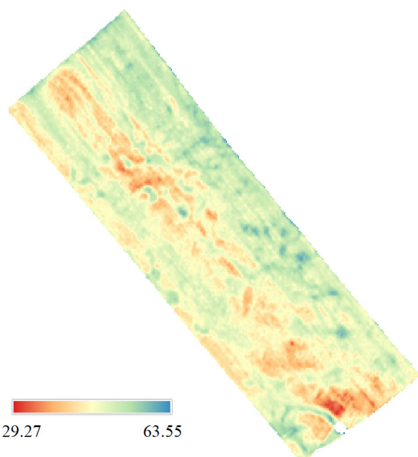
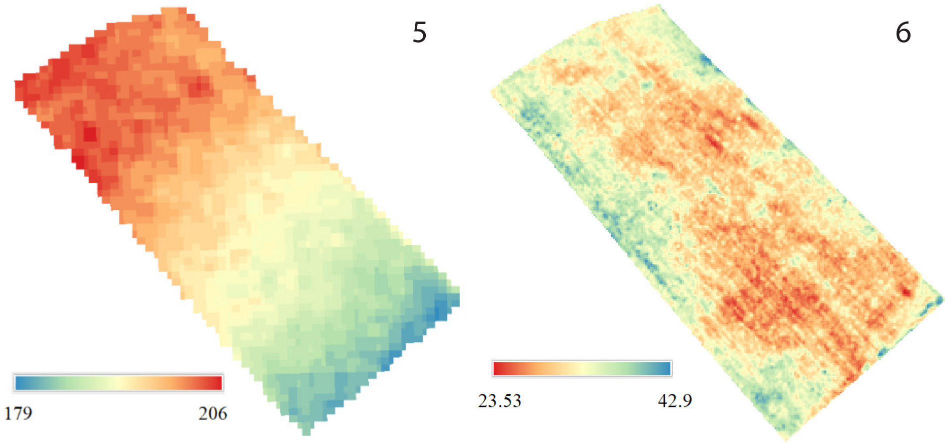
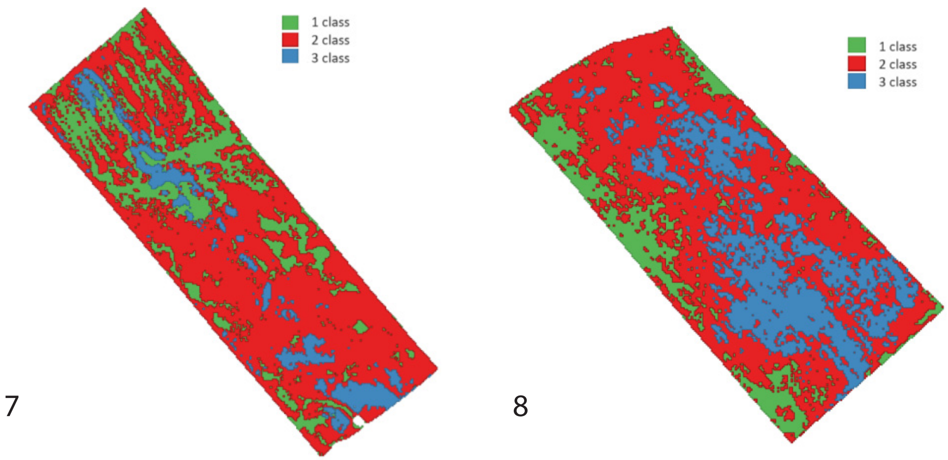


Figure 4. Map of the spatial distribution of the integral values in field No. 47.



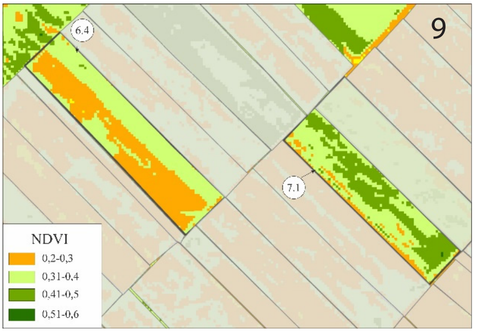
Figures 5–6. 5 – Digital model of the relief in field No. 14. 6 – Map of the spatial distribution of the NDVI integral values in field No. 14.

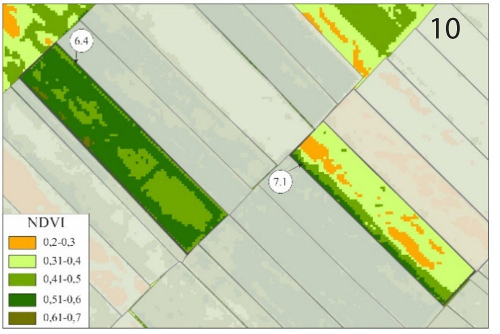
Visualization of task maps to differentiate corn sowing (field No. 47) and sunflower (field no. 14) in the Aleisky district was carried out as follows (Figs. 7-8):



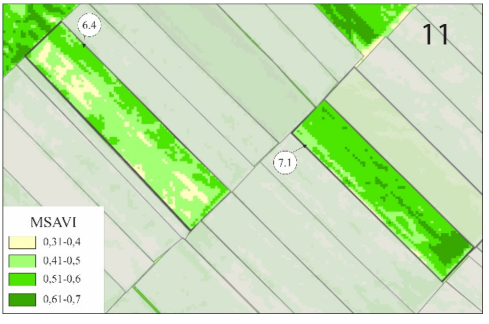
Figures 7–8. 7 – Task map to differentiate corn seed rates in field No. 47. 8 – Task map for differentiated sunflower sowing in field No. 14.

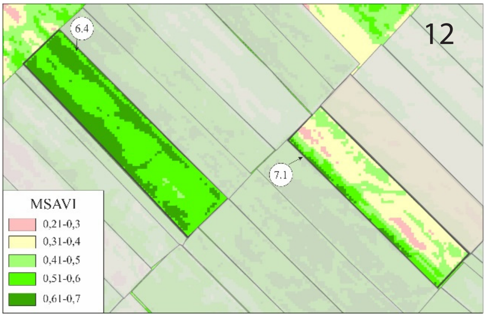
For mapping the fields of the farm in the Pospelikhinsky district (Figs 21–22), images from the Landsat 8 OLI satellite for the period from May to September 2021 were analyzed: the index was calculated and a color synthesized image was obtained. Comparison of the ARVI (productivity) and NDWI (water content) values of wheat agrocenosis showed that productivity is higher in the drier zones of the fields; their boundaries practically coincide. A similar pattern was found for flax crops, although not with a clear distinction for the NDWI values of -0.5 to -0.3. At indices close to 0 (water body boundary), productivity values were minimal. No correlation of this kind was observed for sunflowers (Figs 9–20).



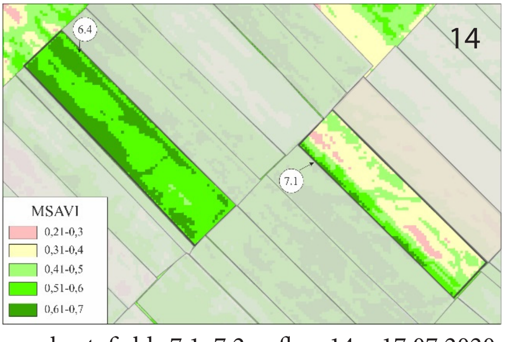


Figures 9–10. 9 – 04.07.2021. Field 6.4. – wheat; field 7.1 – flax. 10 – 17.07.2020. Field 6.4. – sunflower; field 7.1 – wheat.

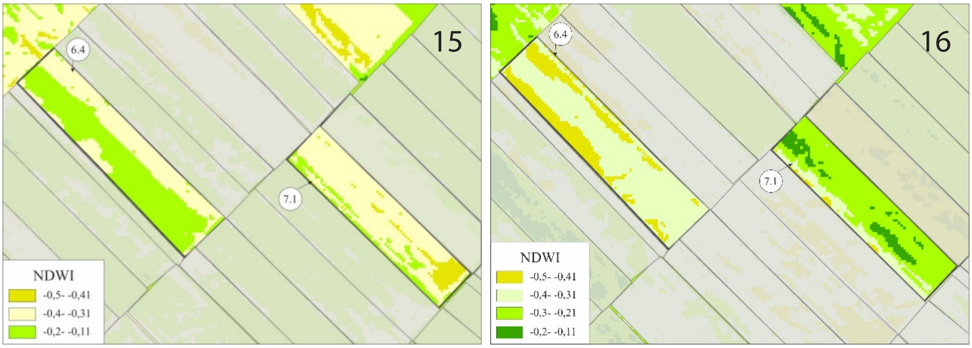




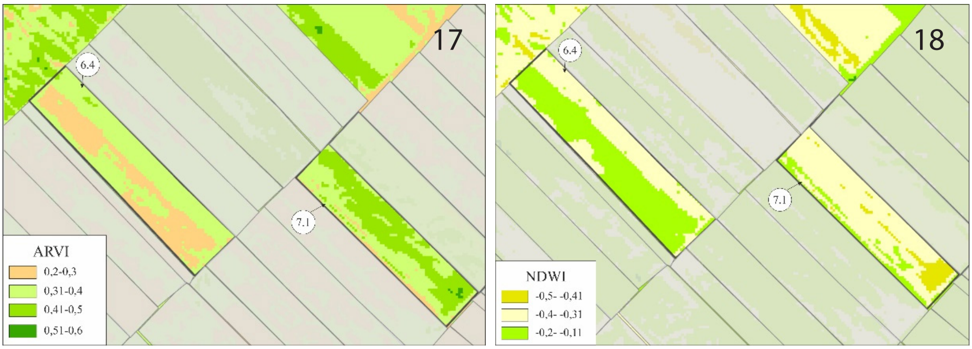
Figures 11–12. 11 – 04.07.2021. Field 6.4. – wheat; field 7.1 – flax. 12 – 17.07.2020. Field 6.4. – sunflower; field 7.1 – wheat.



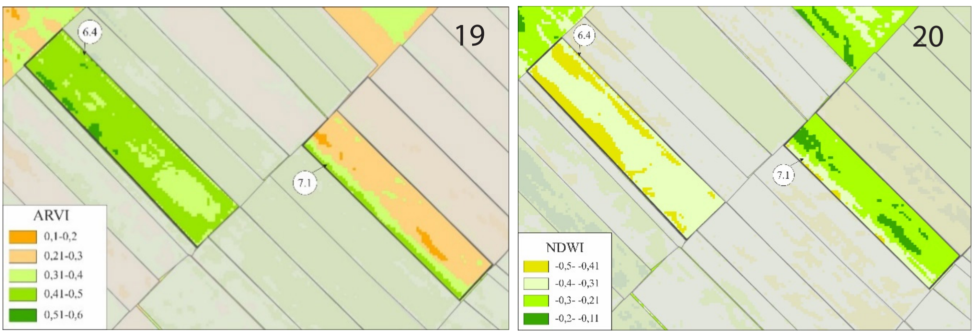
Figures 13–14. 13 – 04.07.2021. Field 6.4. – wheat; fields 7.1, 7.2. – flax. 14 – 17.07.2020. Field 6.4. – sunflower; fields 7.1, 7.2. – wheat.



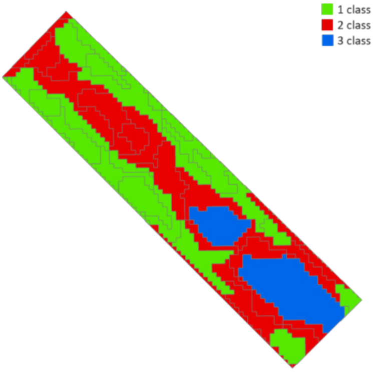
Figures 15–16. 15 – 04.07.2021. Field 6.4. – wheat; field 7.1 – flax. 16 – 17.07.2020. Field 6.4. – sunflower; field 7.1 – wheat.



Figures 17–18. 04.07.2021. Field 6.4. – wheat; field 7.1 – flax.



Figures 19–20. 17.07.2020. Field 6.4. – sunflower; field 7.1 – wheat.



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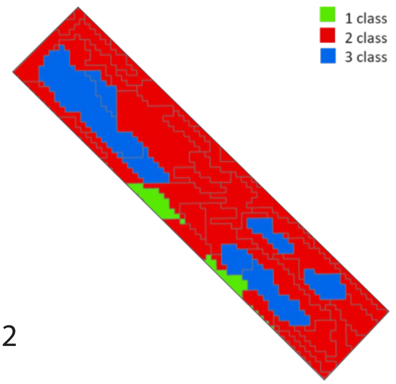

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Figures 21–22. 21 – Task map for the differentiation of the corn seed rate differentiation in field 6.4. 22 – Task map for the differentiation of the sunflower seed rate differentiation in field 7.1.

Analysis of the composition of the soil aggregate and water stability revealed its spatial specificity, which is characterized by the variability of the fractional composition, structural coefficient, and content of water-stable aggregates (Table 3).

Table 3. Soil aggregate composition and water stability

Zone	Soil layer, cm	Content of aggregates of different sizes per soil sample, % of absolutely dry soil mass			Structural coefficient of soil	Content of water-stable aggregates, %
		> 10 mm	10–0.25 mm	< 0.25 mm		
Pospelikhinsky district, no-till						
Corn						
1	0–10	40.1	58.0	1.9	1.4	40.0
	10–20	39.4	59.0	1.5	1.4	26.7
2	0–10	24.2	62.4	13.4	1.7	33.3
	10–20	16.5	75.8	7.7	3.1	26.7
3	0–10	26.6	58.2	15.2	1.4	33.3
	10–20	21.9	69.5	8.6	2.3	20.0
Mean	0–10	30.3	59.5	10.2	1.5	35.6
	10–20	25.9	68.1	5.9	2.1	24.4
Sunflower						
1	0–10	26.6	65.6	7.9	1.9	40.0
	10–20	17.6	75.9	6.5	3.2	20.0
2	0–10	11.9	82.1	6.0	4.6	46.7
	10–20	14.5	79.9	5.6	4.0	40.0
3	0–10	11.7	75.0	13.3	3.0	66.7

Zone	Soil layer, cm	Content of aggregates of different sizes per soil sample, % of absolutely dry soil mass			Structural coefficient of soil	Content of water-stable aggregates, %
		> 10 mm	10–0.25 mm	< 0.25 mm		
	10–20	15.7	77.6	6.7	3.5	40.0
Mean	0–10	16.7	74.2	9.1	2.9	51.1
	10–20	16.0	77.8	6.2	3.5	33.3
Aleisky district, subsurface tillage						
Corn						
1	0–10	10.4	67.0	22.6	2.0	0.0
	10–20	32.0	57.8	10.2	1.4	13.3
2	0–10	14.3	70.8	14.9	2.4	6.7
	10–20	30.6	66.4	3.1	2.0	13.3
3	0–10	25.0	62.0	13.0	1.6	6.7
	10–20	29.2	61.0	9.8	1.6	33.3
Mean	0–10	18.0	66.2	15.8	2.0	4.4
	10–20	29.2	62.1	8.7	1.6	20.0
Sunflower						
1	0–10	18.0	71.6	10.4	2.5	0.0
	10–20	19.6	75.2	5.2	3.0	40.0
2	0–10	29.8	61.5	8.7	1.6	0.0
	10–20	30.9	65.5	3.6	1.9	33.3
3	0–10	19.0	70.4	10.5	2.4	6.7
	10–20	23.2	72.1	4.7	2.6	13.3
Mean	0–10	22.3	67.9	9.9	2.1	2.2
	10–20	24.5	71.0	4.5	2.4	28.9
Statistical characteristics						
$\dot{x}$		22.9	68.3	8.8	2.3	25.0
Cv		33.6	10.2	51.8	35.2	67.4
SDx		1.4	1.2	0.8	0.1	3.0

Note: $\dot{x}$ – mean value, Cv – coefficient of variation, %, SDx – standard error of the mean.

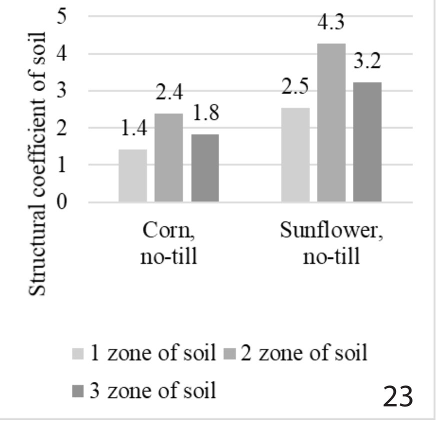
In the upper (0–10 cm) soil horizon, the content of soil fractions of 0.25–10.0 mm in size, which are most agronomically valuable for cultivated plants and exhibit high porosity (more than 45%), mechanical strength, and water resistance, varied from 58.0 to 82.1% with spatial variability equal to 24.1%; this corresponds to a good level of agroecological. In the 10–20 cm layer, the structural state of the soil was also assessed as good (59.0 to 75.8%), but with a lower spatial variability compared to the upper layer, which was 16.8%. The aggregate state of the soil in some zones of the experimental fields was assessed as good, with a structural coefficient of 1.4 units. In most cases (or in most zones), it was assessed as excellent, with a structural coefficient of 1.5 to 4.6, with a range of variation of 3.1 units. Interestingly, this indicator changed distinctly at different soil depths, and its dynamic in the experimental field in the Pospelikhinsky district differed from that in the Aleisky district.

Regarding the content of water-stable aggregates, the soils of the experimental fields (with very rare exceptions) are classified as soils with medium water stability. The dynamics of water stability at different depths of the soil also showed spatial specificity. The granulometric composition of the soil determined by the rolling method (Vadyunina, Korchaina 1986) showed that in all cases we are dealing with clay soil. A more detailed analysis of soil aggregate composition and water stability revealed a certain correlation between structure, one of the main factors of soil fertility (Burlakova and Rassypnov 1990; Gorbyleva et al. 2016), as well as water stability, and the tillage techniques implemented in the study. The soil composition varied at different soil depths and depended on the biological characteristics of the cultivated crops.

The experimental field of corn on the farm in the Pospelikhinsky district cultivated without tilling the soil was characterized by the lowest content of agronomically valuable fractions of 0.25 to 10.0 mm in the upper (0–10 cm) layer, which averaged 59.5%, which was lower than the average values in other fields of 2.7 to 14.7%. At the same time, the field cultivated without tilling the soil showed the highest soil fraction content of 0.25 to 10.0 mm in the 0–10 cm layer in the field experiment; it reached 74.2%. The highest soil fraction content was also observed in the 10–20 cm layer (77.8%), which exceeded that in other fields by 9.7 to 11.6%. It should be noted that no strong correlation was found between soil aggregates and soil fertility, both in the corn field and in the sunflower field. However, the proportion of soil aggregates of 0.25 to 10.0 mm in size increased in the 10–20 cm layer compared to the 0–10 cm layer, probably due to the active use of tillage practices that spray the upper layer applied before no-till techniques.

The experimental fields on the farm in the Pospelikhinsky district showed a higher average value of structural coefficient (2.2), while in corn agrocenosis the lowest values were found in the layer 0–10 cm (1.5), and in sunflower agrocenosis the highest values were found in the layers 2.9 (0–10 cm) and 3.5 (10–20 cm) (Figs 23–25).

The dynamics of the structural coefficient by layers showed a pattern similar to that of the content of agronomically valuable aggregates of 0.25 to 10.0 mm in size: in the 10 to 20 cm layer, the structural coefficient was higher in both the corn field and the sunflower field. Soils in the experimental fields of the Pospelikhinsky district showed an average water stability in the 0–10 cm layer, except for one zone in the sunflower field, which is characterized by the content of water-stable aggregates of 33.3–40.9% in the corn field and 40.0–44.7 in the sunflower field. The 10–20 cm layer also exhibited a water-stable structure along the lower boundary, although the content of water-stable aggregates was 20.0–26.7% lower compared to that in the upper layer. In the experimental fields of the Aleisky district, which uses conventional deep subsurface tillage, some features were revealed in the content and dynamics of soil aggregates and water stability. The indicators of the physical properties were more uniform in values in the fields, and the dynamics by layers was different. In the sunflower field, the proportion of aggregates of 2.5 to 10.0 mm in the 10–20 cm layer was higher compared to the upper layer, similar to the sunflower field in the Pospelikhinsky district, while in the corn field, its content was higher (1.0–9.2%) in the upper layer. At the same time, the upper layer of the corn field was characterized by a higher soil structure coefficient (0.4–0.6%). In the sunflower field, the structural coefficient of the soil in the 10–20 cm layer was 0.2 to 0.5 units higher (Figs 26–28).



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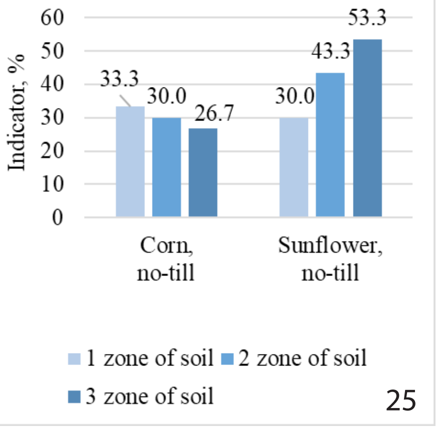

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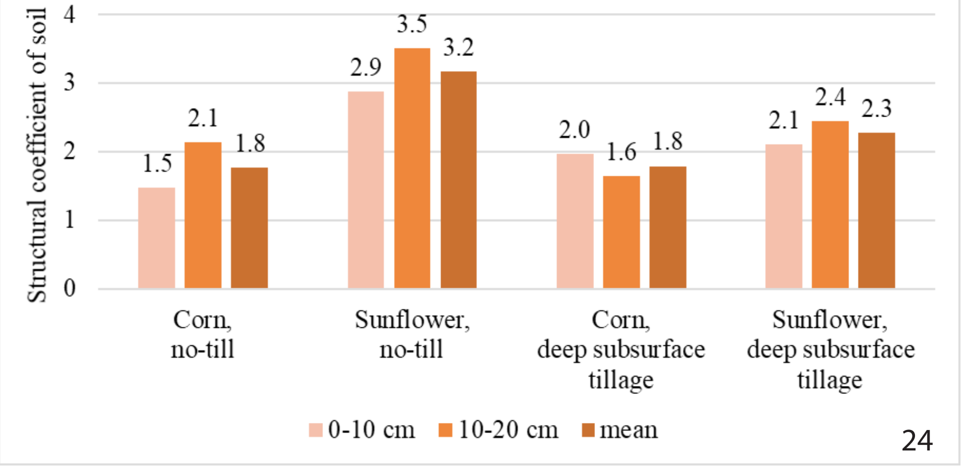

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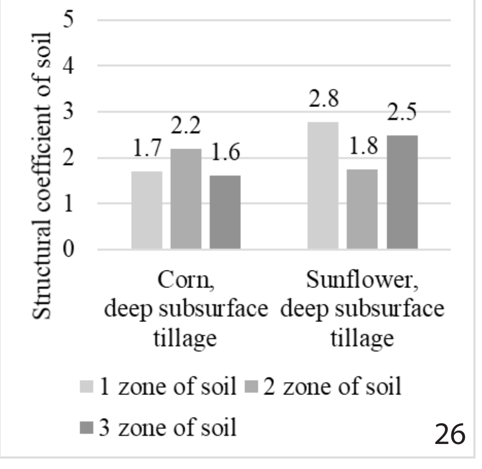
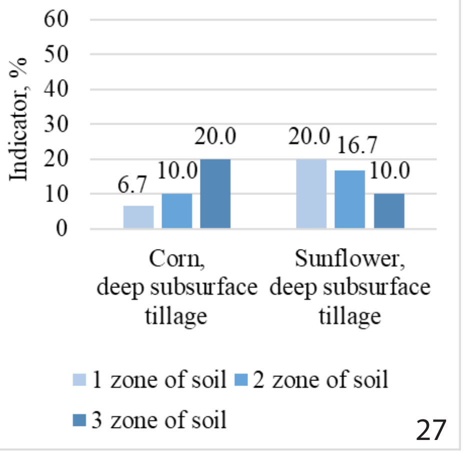
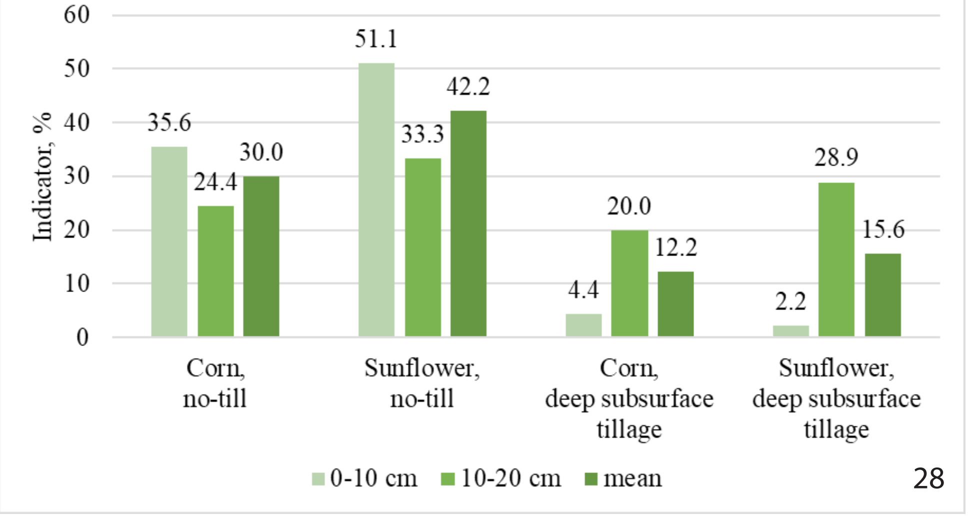
Figures 23–25. 23 – Structural coefficient of the soil in the 0–20 cm layer versus the zone without drilling. 24 – Structural coefficient of the soil in the layers of 0–10 cm and 10–20 cm versus the tillage technique cultivated crops; 25 – Number of water-stable soil aggregates 0.5 to 5 mm in size in the 0 to 20 cm layer versus the field zone under no-till.

Various tillage techniques had the most pronounced effect on the water stability of the soil. Annual deep subsurface tillage and preseed surface tillage (cover harrowing, pre-sowing cultivation) on the farm in the Aleisky district resulted in the formation of a water-unstable structure with a critically low content of water-stable aggregates in the upper layer 0–10 cm (0.0–6.7%) both in the corn field and in the sunflower field. In the layer of 10–20 cm, the content of water stable aggregates approached the level of average water stability, although it remained significantly lower than that under no-till conditions on the farm in the Pospelikhinsky district.







Figures 26–28. 26 – Structural coefficient of soil in the 0–20 cm layer versus the field zone under deep subsurface tillage. 27 – Number of 1 to 5 mm water-stable soil aggregates in the 0–20 cm layer versus the field zone under deep subsurface tillage. 28 – Number of 1 to 5 mm water-stable soil aggregates in size in 0-10 cm and 10-20 cm versus the tillage technique and cultivated crops

Agrochemical analysis of soil samples from experimental fields revealed a very low content of nitrate nitrogen, which is a diagnostic criterion for the nitrification of soils in western Siberia and the main source of nitrogen for field crops. This was reported for all fertility zones in the experimental fields, both in the Pospelikhinsky district and in the Aleisky district. In the upper layer (0–10 cm), the nitrogen content did not exceed 3.0 mg/kg of soil, and in the layer 10–20 cm, it was 2.7 mg/kg of soil. The nitrogen content of the nitrate varied slightly in the identified fertility zones and there was no pronounced sequence of changes in dynamics by soil layers (Tables 4, 5).

Table 4. Agrochemical characteristics of the experimental field, Pospelikhinsky district

	Sampling point	Soil horizon (layer), cm	Nitrate nitrogen content, mg/kg	P_2O_5 content, mg/kg	K_2O content, mg/kg	Humus, %
Corn	Fertility grade 1	0–10	2.1	140.2	195.8	4.1
		10–20	1.5	135.0	107.8	4.0
	Fertility grade 2	0–10	2.5	135.0	227.2	4.8
		10–20	1.9	117.2	87.9	3.8
	Fertility grade 3	0–10	2.1	142.7	124.5	4.1
		10–20	1.4	168.8	156.3	3.9
Sunflower	Fertility grade 1	0–10	1.9	221.5	284.9	4.3
		10–20	1.7	163.3	94.0	3.6
	Fertility grade 2	0–10	2.0	175.6	236.0	4.2
		10–20	1.8	221.7	107.2	4.1
	Fertility grade 3	0–10	2.4	145.5	114.1	3.9
		10–20	2.0	129.4	94.2	3.9

Note: The sampling point/fertility grade in the table corresponds to the fertility grades indicated in Figs 1–4: grade 1 – increased fertility, grade 2 – normal (moderate) fertility, grade 3 – decreased fertility.

Table 5. Agrochemical characteristics of the experimental field, Aleisky district

	Sampling point	Soil horizon (layer), cm	Nitrate nitrogen content, mg/kg	P_2O_5 content, mg/kg	K_2O content, mg/kg	Humus, %
Sunflower	Fertility grade 1	0–10	1.6	151.5	122.6	3.8
		10–20	1.8	149.4	102.2	3.4
	Fertility grade 2	0–10	2.1	128.9	114.7	3.3
		10–20	2.1	129.1	120.5	3.5
	Fertility grade 3	0–10	3.0	150.4	161.7	3.1
		10–20	1.9	155.8	101.3	3.9

	Sampling point	Soil horizon (layer), cm	Nitrate nitrogen content, mg/kg	P_2O_5 content, mg/kg	K_2O content, mg/kg	Humus, %
Corn	Fertility grade 1	0–10	1.7	126.9	205.8	3.7
		10–20	1.3	116.6	144.1	3.4
	Fertility grade 2	0–10	1.5	135.7	174.2	3.5
		10–20	1.6	127.1	153.7	3.2
	Fertility grade 3	0–10	2.2	64.8	154.3	3.4
		10–20	2.7	62.4	101.3	3.1

Note: The sampling point/fertility grade in the table corresponds to the fertility grades indicated in Figs 1–4: grade 1 – increased fertility, grade 2 – normal (moderate) fertility, grade 3 – decreased fertility.

However, the nitrogen nitrate determined mainly by the nitrification ability of the soil, which depends on the content of humus, total nitrogen and microaggregate state of the soil, showed a tendency to increase under deep subsurface tillage and amounted to 0.03 mg/kg of soil on average in soil layers and fertility zones. This is probably due to scientific theory on more favorable nitrification conditions under deep tillage, particularly under mouldboard plowing. Minimal or no tillage applied reduces the intensity of nitrification 1.5 times or more, which is associated with a marked decrease in nitrification in the lower part of the soil profile.

In contrast to soil nitrification, an increased content of mobile phosphorus (100 to 150 mg P_2O_5/kg of soil) and high (150 to 200 mg P_2O_5/kg of soil) was found in the experimental fields, with the exception of the fertility zone 3 of the corn field in the Aleisky district, where it was medium level (50–100 mg P_2O_5/kg of soil). The increased content of mobile phosphorus in the soil of the experimental fields is obviously associated with incomplete weathering of the rocks and minerals that are predominantly composed of this element, as well as its high gross reserves in the soil, which are characteristic of chernozems formed on sedimentary rocks of marine origin.

Higher mobile phosphorus in soil without tillage, on average 163.3 mg of P_2O_5/kg of soil in the 0–10 cm layer and 171.5 mg of P_2O_5/kg of soil in the 10–20 cm layer. In the experimental field of the Aleisky district, its content in these layers was lower by 54.2–69.5 mg of P_2O_5 / kg of soil, although this difference could be due not only to soil tillage, but also to the characteristics of the parent rock, the nature of soil formation, and previous agricultural practices associated with mineral fertilizers. Numerous researchers report that the application of NPK fertilizer in ratios that do not correspond to the biological characteristics of crops could lead to an excessive accumulation of individual elements in the soil, especially phosphorus.

A higher amount of exchangeable potassium was found in the experimental field of the Pospelikhinsky district (152.5 mg K_2O/kg of soil), although in the field of the Aleisky district its average content (138.0 mg K_2O/kg of soil) corresponded to a high amount (120–180 mg K20/kg of soil). Regarding the exchangeable potassium content by layers and fertility zones, its dynamic pattern shows a more obvious decrease in its concentration in the 20–30 cm layer compared to the 0–10 cm layer, as well as in fertility zones 2 and 3 compared to zone 1.

The strongest correlation was found between the spatial differentiation of the fertility zones and the content of the humus. In the corn field in the Aleisky district with an average humus content of 3.44% in the 0–20 cm layer, the negative dynamics of its content in fertility zones (from 1 to 3) was evident in both the 0–10 cm layer of (3.7-3.5-3.4%) and the layer 10–20 cm (3.4-3.2-3.1%). In the sunflower field, similar dynamics was observed in the layer 0–10 cm (3.8-3.3-3.1%).

In the Pospelikhinsky district characterized by a higher amount of organic matter (4.06% on average) in sunflower experimental fields, a similar correlation between fertility zones and the dynamics of the humus content was found only in the layer of 0–10 cm (4.3-4.2-3.9%). No correlation of this kind was observed in the 10–20 cm layer and in both layers of the corn field, which is obviously due to a more uniform distribution of organic matter throughout the profile of the 0–20 cm layer under mulching that excludes soil mixing by deep tillage. Soil moisture in fertility zones and moisture reserves in the meter layer were evaluated from 3 to 4 May and 10 to 11 June 2023. The results are summarized in Tables 6 and 7.

Table 6. Data on soil moisture and moisture reserves with respect to soil fertility zones of experimental fields (3 May 2023)

Field zone / fertilization grade	Volumetric soil moisture content at different soil depths, cm (%)										W0-100, mm
	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100	
SPK Znamya Rodiny (Agricultural Production Cooperative). Crop – sunflower											
1	41.7	26.7	29.5	34.3	41.5	37.9	36.1	37.3	44.2	44.2	373.4
2	22.9	22.7	26.3	20.3	16.4	15.2	19.4	15.7	15.7	17.3	191.9
3	23.8	20.6	25.1	17.1	21.6	22.7	19.1	18.8	21.3	20.4	210.5
SPK Znamya Rodiny (Agricultural Production Cooperative). Crop – corn											
1	28.2	23.4	23.5	25.1	18.6	23.3	22.2	21.0	19.8	17.9	223.0
2	27.3	22.2	19.8	20.3	16.9	16.2	10.8	19.5	22.1	19.5	194.6
3	23.1	22.5	22.6	19.9	25.1	18.9	19.1	17.3	22.0	16.7	207.2
OOO Zolotaya Osen (Limited Liability Company). Crop – sunflower											
1	20.5	54.7	26.8	26.0	26.8	24.0	17.4	18.0	17.0	15.9	217.1
2	25.4	23.2	31.7	29.0	30.9	30.6	31.9	33.6	31.8	29.4	297.5
3	20.3	25.7	26.3	27.3	25.6	24.2	22.2	19.1	17.3	16.4	224.4
OOO Zolotaya Osen (Limited Liability Company). Crop – corn											
1	27.0	27.1	30.8	32.4	35.5	37.9	33.2	29.8	28.3	28.7	310.7
2	26.6	31.6	30.4	30.3	26.3	24.3	18.8	16.5	15.9	18.5	239.2

Field zone / fertilization grade	Volumetric soil moisture content at different soil depths, cm (%)										W0-100, mm
	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100	
3	19.4	30.2	29.8	29.3	29.2	31.1	28.1	24.9	31.2	26.4	279.6

Note: The field zones in the table correspond to the fertility grades indicated in Figs 6, 7, 20, 21: grade 1 – increased fertility, grade 2 – normal (moderate) fertility, grade 3 – decreased fertility.

Table 7. Data on soil moisture and moisture reserves in fertility zones of experimental fields (10 June 2023)

Zone	Volumetric soil moisture content at different soil depths, cm (%)										W0-100, mm
	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100	
SPK Znamya Rodiny (Agricultural Production Cooperative). Crop – sunflower											
1.1	17.1	19.0	26.6	25.9	21.2	26.1	20.5	20.1	20.2	19.0	215.7
2.1	25.6	17.8	23.5	19.8	25.0	21.6	18.4	18.7	20.3	20.3	211.0
2.2	22.4	22.9	23.0	20.4	22.1	20.6	20.0	20.3	19.3	20.8	211.8
2.3	14.3	16.6	17.7	23.1	22.6	18.6	15.2	18.7	17.2	17.0	181.0
3.1	17.0	19.8	20.5	20.7	24.5	20.9	20.0	18.9	19.3	18.7	200.3
3.2	13.8	15.0	24.6	25.2	28.8	28.5	25.9	24.2	24.1	20.6	230.7
3.3	17.1	17.4	20.7	25.6	27.0	28.5	26.9	21.6	25.1	24.4	234.3
SPK Znamya Rodiny (Agricultural Production Cooperative). Crop – corn											
1.1	16.7	17.3	20.3	21.6	24.9	25.9	26.6	23.9	23.4	25.2	225.8
1.2	10.3	14.1	13.9	16.9	19.8	23.1	25.1	27.4	24.2	23.3	198.1
2.1	21.8	14.5	19.8	23.5	18.7	21.0	20.9	20.6	18.0	19.1	178.8
2.2	9.5	11.9	11.3	14.6	16.7	18.9	22.9	20.4	20.7	19.1	166.0
2.3	11.3	13.0	13.5	14.8	19.3	24.3	22.6	23.0	18.2	19.2	179.2
3.1	16.1	18.4	19.6	19.8	23.0	21.2	23.4	23.7	22.4	21.5	209.1
3.2	16.6	10.5	12.2	17.4	18.1	19.3	19.2	19.5	20.1	22.1	175.0
OOO Zolotaya Osen (Limited Liability Company). Crop – sunflower											
1.1	17.0	13.5	11.9	17.5	13.7	20.3	21.2	22.6	22.7	18.7	179.1
1.2	18.6	12.0	18.5	20.9	21.4	23.1	24.0	24.4	24.7	22.9	210.5
1.3	15.5	12.6	15.8	22.8	20.7	24.0	22.3	21.5	17.7	19.5	192.4
2.1	18.2	10.0	14.1	23.0	22.1	20.2	20.7	16.1	23.3	24.1	191.8
2.2	7.1	11.9	11.6	17.0	20.4	19.5	20.6	22.1	20.3	18.6	169.1
2.3	12.4	14.1	13.6	17.0	18.5	16.1	18.9	19.6	16.5	17.0	163.7
3.1	19.5	10.8	21.0	19.5	18.6	17.8	19.2	18.9	21.1	17.2	183.6
3.2	17.1	13.7	11.3	17.8	16.1	19.2	18.1	21.1	23.1	20.9	178.4

Zone	Volumetric soil moisture content at different soil depths, cm (%) 0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100	W0-100, mm
3.3	15.5	12.6	19.9	19.4	20.8	20.5	21.2	22.8	21.9	19.6	194.2
OOO Zolotaya Osen (Limited Liability Company). Crop – corn											
1.1	10.6	9.5	20.6	20.5	22.6	19.8	22.4	21.2	21.3	22.1	190.6
1.2	16.7	16.3	18.9	21.4	20.5	21.8	21.5	19.8	17.3	17.7	191.9
1.3	12.6	14.7	20.2	23.0	23.5	23.0	20.9	22.0	22.6	20.0	202.5
2.1	16.3	12.9	19.0	15.4	19.0	20.4	15.9	18.1	20.6	20.3	177.9
2.2	11.8	10.0	12.6	11.5	17.0	22.9	21.8	18.2	20.5	20.5	166.8
2.3	14.3	14.1	15.7	20.9	23.3	16.7	21.0	20.3	19.6	19.7	185.6
3.2	17.7	13.8	16.4	22.3	18.8	18.4	23.3	21.9	19.4	18.2	190.2
3.3	8.3	10.2	19.0	15.9	21.7	18.2	20.3	24.0	21.6	21.3	180.5
4.1	13.9	11.8	19.6	24.6	21.5	17.4	20.2	19.0	20.4	17.5	185.9
4.2	21.5	14.7	16.5	20.3	20.6	20.8	20.0	19.7	21.9	19.5	195.5
4.3	8.3	9.4	10.5	15.8	19.0	16.8	15.0	17.2	16.3	16.6	144.9

Note: The field zones in the table correspond to the fertility grades indicated in Figs 6, 7, 20, 21.

The analysis revealed that the average soil moisture in layers up to 1 meter in spring (May 3) in different fertility zones of the experimental fields varied significantly and ranged between 19.2 and 37.4%. Soil moisture Soil moisture was found to vary at different soil depths and amounted to 11.4 to 25.3%. As a result, the differences in total moisture reserves in the meter layer in different fertility zones ranged from 28.4 mm to 181.5 mm. This indicates a significant effect of soil fertility grades on moisture accumulation and distribution at different soil depths in spring and, as a consequence, on the soil moisture regime during the growing season and the yield of the crop. On 10 June, the average soil moisture in layers of up to 1 meter in different fertility zones of the experimental fields decreased significantly and was 14.5-21.6%. Soil moisture was found to vary at different soil depths (6.2 to 29.5%), and differences in total moisture reserves in the meter layer in different fertility zones decreased from 46.8 to 59.8 mm. Therefore, soil moisture was found to be uniform in values at different depths of the soil in areas of different fertility grade.

Discussion

The construction of productivity and moisture maps in precision agriculture with respect to vegetation indices based on decision tree classification is a frontier in agribusiness to address issues of seed rate differentiation, local fertilization, crop rotation, and high-quality agrotechnical measures. One of the main indicators for assessing soil fertility is the differentiation of the content of humus and the main nutrients in the soil. In this regard, differentiated fertilization is crucial for precision agriculture. Most of the factors affecting the state of plants and soil characteristics are zonal and require a more qualified integrated approach and interpretation of data obtained (UAVs, satellite images, soil analysis). Numerous researchers report that an integrated approach is the most efficient for precision agriculture.

In addition to specialized equipment, differentiated fertilization requires an appropriate algorithm to dose fertilizers in zones of heterogeneous soil fertility based on objective data. NDVI, MSAVI2, ARVI, and NDWI were used to develop the algorithm to identify soil fertility zones and map potential yields. There are certain limitations in using NDVI:

- the impossibility of using data without preliminary radiometric correction (calibration);
- errors caused by weather conditions, in particular, heavy cloud cover. Their effect can be partially eliminated by coefficients and composite images improved with NDVI series obtained over several days, weeks, or months. Averaged values minimize the effect of random and some systematic errors;
- the need for comparing the obtained results with the data previously collected from experimental fields with regard to seasonal environmental and climatic indicators from both the image and experimental fields for the current date of data collection;
- the possibility of using the image taken only during the growing season in the study area. Since NDVI depends on the amount of photosynthetic biomass, it cannot be applied to images obtained in the period of weakened vegetation (Cherepanov 2011).

It should be noted that MSAVI2, the second modified soil-adjusted vegetation index, was created by Qi et al. (1994) as a recursion of MSAVI. Basically, the authors used an iterative process and replaced MSAVI(n-1) as the L factor in MSAVI(n). They inductively solve an iteration where MSAVI(n) = MSAVI(n-1). The process eliminates the need to precalculate WDVI and NDVI and determine the soil line. The study revealed that one image could contain soils with different reflection spectra. Furthermore, if the assumption about iso-vegetation lines (parallel or intercepted at the origin) is incorrect, changes in soil moisture (which move along iso-vegetation lines) will yield incorrect values for the vegetation index. The problem of soil noise is most acute in the case of low vegetation cover. These indices attempt to reduce soil noise by changing the behavior of isovegetation lines.

The blue band is more susceptible to atmospheric scattering than the red band, mainly because of its shorter wavelength. Thus, the atmospherically resistant vegetation index (ARVI) introduced by Kaufman and Tanre (1992) uses different scattering characteristics in the blue and red bands to provide data on atmospheric opacity. Thus, the normalized difference water index (NDWI) introduced by Gao (1996) is less sensitive to atmospheric effects than the NDVI. Since the NDWI does not completely eliminate the background effects of soil reflection, it should be considered as an independent vegetation index. It should be noted that it does not replace NDVI. The NDWI uses the channel centered approximately at 1.24 μm (Kravtsov 2010) that can be found at the edge of the water absorption band, while the channel centered approximately at 0.86 μm is insensitive to changes in water content. The soil effect is minimized more effectively due to the fact that the NDWI channel centered approximately at 1.24 μm is more sensitive to soil moisture than the NDII channel centered approximately at 1.64 μm.

Conclusion

Based on the analysis of long-term data, the main factors that affect the level of natural soil fertility were determined in different field zones (humus content, moisture reserves, farming technique), the fertility zones were identified and the potential crop yield was assessed. The data from the field experiment were used to quantify the variability of the nutrient content, the structural composition of the soil, and the moisture content at different soil depths for different tillage techniques. A methodology was proposed to construct task maps for differentiated sowing and fertilization. The constructed maps confirm the fertility zones and their boundaries identified on a series of long-term field data.

The soil cover in the experimental fields was characterized by spatial variability in the fractional composition, structural coefficient, and content of water-stable aggregates. The agrophysical properties of the soil cover depended on the tillage technique and the biological characteristics of the cultivated crop. Fertility zones and soil aggregate composition did not show a strong correlation; however, the proportion of soil aggregates of 0.25 to 10.0 mm in size in the 10–20 cm layer increased compared to that in the 0–10 cm layer. This is probably due to actively used tillage practices spraying the upper layer, including those applied prior to no-tilling on the farm in the Pospelikhinsky district. Annual deep subsurface tillage and presown surface tillage (cover harrowing, presown cultivation) lead to the formation of a water-instable structure with a critically low content of water-stable aggregates in the layer of 0-10 cm (0.0–6.7%).

The soils in the experimental fields were characterized by very low nitrate nitrogen not exceeding 3.0 mg/kg of soil in the layer 0–10 cm and 2.7 mg/kg of soil in the layer of 10–20 cm. Its content varied slightly in different fertility zones and no dynamic pattern could be observed at different soil depths. At the same time, the content of nitrate nitrogen was found to increase under deep subsurface tillage. The content of available phosphorus and exchangeable potassium in the soil of the experimental fields was assessed as increased and high. The no-till technique increased the content of mobile phosphorus and exchangeable potassium. Compared to the content of mineral nutritional elements (NPK) in soil content, the humus showed the strongest correlation with spatial differentiation of fertility zones.

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