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Models of Winter Wheat Yield Based on Calcareous Chernozem Fertility Parameters

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Abstract: The use of polyelement diagnostics and regression analysis for predicting the yield of winter wheat at different stages of vegetation is considered. It has been established that the prediction and integrated assessment of grain yield and quality should be performed with consideration for the balance of macro-and micronutrients in the grain and the aboveground biomass of plants. Possibility of predicting the contents of macro-and micronutrients in wheat grain from the chemical composition of plants at the shooting stage has been revealed. Scientifically based recommendations are presented for managing the grain yield and quality of winter wheat.

Keywords: Winter Wheat, Plant Chemical Composition, Multinutrient Diagnostics, Plant Nutrition Balance

Introduction

The current development stage of monitoring systems is characterized by active integration and globalization processes. The most known of these processes is the development of the Global Earth Observation System of Systems (GEOSS), which integrates data of remote sensing, in situ observations and models for the development of support systems for management decision making within the framework of food safety (Bereza *et al*., 2015; Kogan *et al*., 2013). The concept of agro monitoring includes two main components: the estimation of crop areas and the prediction of crop yield (Kolotii, 2012).

The prediction of agricultural crop yields is of great importance for the organization of current crop production, because it makes possible to select and plan technological operations of crop tending; determine the necessary volume and range of fertilizers, plant protection agents and other materials and the scope of harvesting operations; and calculate the potential income of the enterprise (Ziganshin and Sharifullin, 1974).

The use of models allows agronomists and farmers to develop sustainable agricultural systems, which are adapted to the less favorable agro-ecological conditions (Spiertz, 2013). Increased agricultural sustainability is one of the main directions the economic efficiency of agricultural production and related industries improvement, which consists of increasing profits and profitability, efficiency of production and use of resources.

One of the most common approaches to predicting the crop yield is the application of empirical regression models, which relate the crop yield to some predictors (e.g., satellite-determined biomass parameters) and usually need no large volume of input data.

Cereals are the main strategic crops for many countries. In spite of the great experience in their growing, the formation of stable yield and crop page has faced problems up to now, which is primarily related to the environmental factors and growing conditions (Schillinger *et al*., 2012; Anderson *et al*., 2010). The prediction of yield is of special importance for winter cereals, including soft winter wheat as the major food crop in the Rostov oblast and the entire Russia.

The accuracy of predicting the crop yield few months before the beginning of harvest is of importance for the solution of global, national and regional problems; therefore, numerous works deal with this issue (Kogan *et al*., 2011; Ryabchun, 2014; Marenich and Shkurko, 2014; Kildyushkin *et al*., 2010). However, the available works were mainly aimed at predicting the yield on the country level (Kussul *et al*., 2012; Kochetkova *et al*., 2014) or illustrating the prediction potential for separate regions (Zinchenko, 2005; Vinogradov, 2014). The prediction of crop yield on the level of separate soil taxons received less attention.

The aim of this study was to develop an integral indicator system for predicting the grain yield and quality of winter wheat grown on calcareous chernozems.

Materials and Methods

Long-term field studies were performed on the production plantations of winter wheat in the Rostov oblast.

For the formation of the experimental data base, soil and plant samples were simultaneously taken from microplots according to the procedure described in methodological recommendations on the regulation of macro- and micronutrient ratios in plants according to the ISOD system (El'nikov and Prokhorov, 1989).

Within the production plantation of winter wheat, small plots of 2×2 m were annually selected along the field diagonal at the shooting stage. On these plots, plant and soil samples were taken and plant productivity was determined in triplicate at the shooting and full maturity stages. The grain yield was calculated in t/ha. Soil samples were taken at a depth of the plow layer (0-25 cm) simultaneously with the plant samples: total aboveground biomass at the shooting stage and grain at the full maturity stage.

The content of humus was determined by the TsINAO modification of the Tyurin method (GOST 26213). The method involves the oxidation of organic matter with a solution of potassium dichromate in sulfuric acid. The pH of water extract was determined by the ionometric method (Mineev, 2001). Available phosphorus and exchangeable potassium were extracted with 1% ammonium carbonate solution (pH 9.0) at a soil: Solution ratio of 1: 20 (GOST 26205). The determination of exchangeable calcium and magnesium was performed using a 1.0 N sodium chloride solution (pH 6.5) with complexometric detection.

At the determination of nitrogen in plant samples, the mineralization of material was performed in concentrated sulfuric acid at a ratio of 1: 10 in the presence of a mixed catalyst (10.0 g $CuSO_4$ + 100.0 g K_2SO_4 + 2.0 gSe). The percentage of protein in winter wheat grain was calculated by multiplying the content of nitrogen by a scaling factor of 5.7 (GOST 10846, 1991). The content of crude gluten was determined in a 25-g sample of ground grain with the addition of 14.0 mL of water and mixing to a homogeneous state (GOST 13586.1, 1968).

The minimum number of observations for each type of analysis was 50 annually during four years of study.

The developed database was used for studying the response of plants to the intra field heterogeneity of growing conditions by statistical methods (correlation and regression analyses). For the more complete description of this response and the study of the balance of changes in different parameters, the equations of the Integrated System of On-Line Diagnostics (ISOD) were used (El'nikov, 2002).

The ISOD makes it possible to analyze the relationship between the changes in plant or soil parameters and the changes in any response parameter (e.g., protein content). The ISOD can also rank the studied chemical elements by the degree of deficiency or excess and distinguish antagonist elements and leader (dictator) elements most affecting the response parameter.

In the ISOD, the plant supply with each element is denoted by index (iR).

If the iR of an element is lower than 1, the relative level of the element supply, as well as the absolute content in the case of the linear relationship, is decreased compared to its maximum value in the analyzed data set (established norm). Correspondingly, if the iR value is higher than 1, the absolute or relative element supply is excessive. If the balance of the studied parameters does not change against the established norm, their iR values will be equal to 1 under the studied conditions, which indicates the absence of linear relationship between their changes and the change of the selected criterion (e.g., protein content). Alternatively, the higher the response of the studied crop to the changes in the relative and absolute levels of the studied systems of diagnostic criteria, the higher the number of parameters with indices different from 1. Thus, a conclusion may be drawn about the sensitivity of plants to changes in the controlled parameters and the degree of their deficiency compared to the established norm.

Results of Study

Long-term data showed that the arable calcareous chernozems are characterized by the high spatial heterogeneity of agrochemical parameters and winter wheat productivity (Table 1).

The analysis of the database revealed relationships of winter wheat grain yield and quality with the physicochemical properties of soil and the chemical compositions of plants. The separate state parameters of soil and plants, as well as their ratios, were considered (Fig. 1-7).

For the prediction of grain yield and quality of winter wheat grown on calcareous chernozem, the following models were obtained:

$$\begin{aligned} U_t &= -132.00 + 5.65N - 9.76Si + 13.65P - 12.60K \\ &+ 0.20Mn - 0.05Fe - 0.47Ni + 0.16Sr + 0.56Cu + 3.74Ps \\ &- 2.16Ks + 75.80Ks/Cas + 3.24Cas/Mgs + 3.40(Cas + Mgs) \\ &+ 3.75Fe/Mn - 8.40N/K + 1.64K/P,\ F = 2.1,\ R^2 = 0.70 \end{aligned} \quad (1)$$

$$\begin{aligned} U_t &= 40.4 + 9.1N - 7.9Si - 7.9K \\ &+ 4.3Ps - 11.1\ N/K,\ F = 2.03,\ R^2 = 0.55 \end{aligned} \quad (2)$$

$$\begin{aligned} Prot(\%) &= 12.7 - 0.31Ps + 0.06Ks + 1.55Ps/G \\ &+ 0.54N - 0.73N/K - 4.2Cl - 0.012Mn - 0.74P \\ &+ 0.011Fe/Zn,\ F = 3.5,\ R^2 = 0.8 \end{aligned} \quad (3)$$

$$\text{Prot}\ (\%) = 11.3 + 0.06\text{Ks} + 0.46\text{N},\ F = 3.4,\ R^2 = 0.7 \quad (4)$$

$$\text{Gl}(\%) = 30.1 + 3.2\ \text{N} + 0.18\ \text{M} - 0.48\ \text{Ps} - 2.5\ \text{P} - 1.6\ \text{Mgs} - 1.6\ \text{K} + 0.14\ \text{Zn},\ F = 1.8,\ R^2 = 0.5 \quad (5)$$

The response of the crop yield to the changes in soil agrochemical parameters and their ratios (Table 2) was studied using model (1) and assessment criteria for the growing conditions of winter wheat on calcareous chernozem were determined (Table 3).

Discussion

It should be emphasized that the spatial heterogeneity is typical not only for separate soil parameters, but also for their balance (or ratios). Presently, the balance of soil properties is not considered at the assessment of their fertility. Available data indicate that the ratios of some physico-chemical properties can be leading integrated indicators of soil suitability for growing separate crops, especially on the soils with pronounced microheterogeneity (El'nikov and Savvinva, 2006). It was revealed that the ratios between the essential soil properties in the plow layer have wider variation amplitudes than their absolute values. So, the maximum contents of exchangeable potassium and calcium in the studied chernozem exceed their minimum contents by 1.9 and 1.3 times, respectively, while the extreme ratios of these parameters (Ks/Cas) differs by 3.1 times. This example indicates that the ratio of the parameters more adequately reflects the microheterogeneity of soil than their separate values. The high spatial variation is also typical for the elemental composition of the above-ground wheat biomass at the shooting stage.

It raises the question about the degree of agreement between the variation of wheat productivity parameters and the chemical composition of its above-ground biomass, on one side and the above parameters, on the other side. To answer this question, the multiple regression analysis of the long-term data base was performed, which revealed clear correlations between the yield of wheat grain and some soil properties and their pair ratios (Fig. 1 and 2).

Raun *et al*. (2001) indicated that the maximum yield of winter wheat grain can be obtained only in the absence of limitations for all growth factors.

That is why the highly reliable and stable correlations were observed for the yield of winter wheat grain only at the simultaneous consideration of numerous parameters characterizing the state of plants and soil: the contents of N, Si, P, K (%), Fe, Ni, Cu, Mn, Sr and Zn (mg/kg); the Fe/Mn, N/K, K/P ratios in the above-ground plant biomass at the shooting stage; the contents of humus (%), available phosphorus and exchangeable potassium (mg/kg soil); and the contents of exchangeable calcium and total exchangeable bases (mmol(+)/100 g) in the plow player of soil.

We define these parameters as a system of indicators directly or indirectly characterizing the conditions of wheat growing. The high information value of the above parameters is clear, because they are more closely related to the agrochemical features of calcareous chernozem. The new is the inclusion of the Sr content in the above-ground wheat biomass at the shooting stage into the system of indicators. The content of Sr in plants positively correlates with the content of calcium (Fig. 3).

This can explain in part the high diagnostic value of the Sr content in the aboveground biomass of plants on the studied soils as an indicator of the wheat growing conditions (Mineev, 2005; Biryukova *et al*., 2005). From our data, the contents of Ca and Sr and their ratio in the above-ground plant biomass (at the shooting stage) also affects the accumulation of phosphorus in wheat grain. The efficiency of using the above parameters as indicators of wheat growth conditions was confirmed by multiple regression analysis. The model best describing the agrochemical features of calcareous chernozem and most accurately predicting the yield of winter wheat grain included 17 indicator parameters: Model (1).

A simpler model (2) was developed for the preliminary express prediction.

The agreement between the yields predicted from model (1) and the factual yields is shown in Fig. 4.

Of special interest is the study of changes in the crop yield predicted using the integrated system of indicators for different gradations of the agrochemical parameters of soil (Table 2).

The change of wheat productivity among the gradations of soil properties and their ratios is found to be not chaotic and can be described by a nonlinear curve. This allows defining the permissible and impermissible changes in the soil properties for winter wheat. We define the impermissible changes of soil properties as the changes corresponding to a decrease of wheat grain yield by 15% and more compared to the maximum value. An especially abrupt decrease of the winter wheat yield is observed on the soils with $pH > 7.4$. The soils with the narrow ratios between available phosphorus and humus (<0.8) and the ratios between exchangeable potassium and adsorbed calcium Ks/Cas higher than 1.9 or lower than 1.0 are also unfavorable for wheat growing.

In each group of soil parameters, the decrease of the yield is due to the effect of the studied soil property on the nutrition of plants (Mansouri *et al*., 2014; Liu *et al*., 2006; Hasegawaa and Denison, 2006). This disturbance can result from the changes in the content of one or several chemical elements in plants, e.g., the N/K ratio (Fig. 5).

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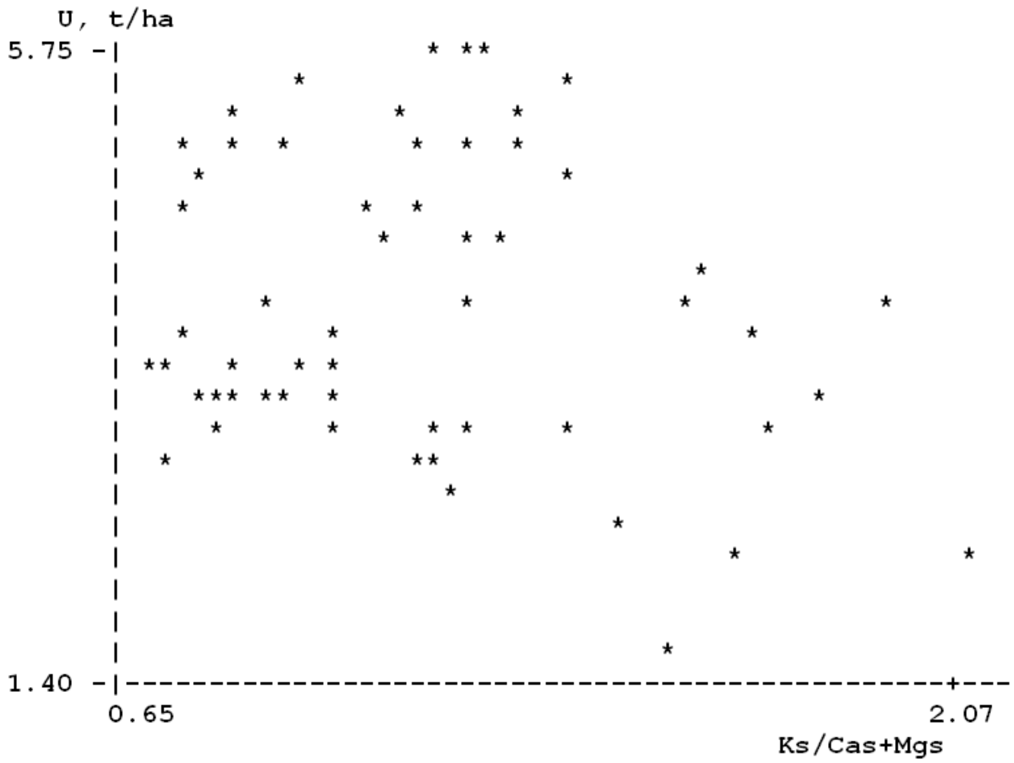

Fig. 1. Yield of winter wheat grain as a function of the ratio of exchangeable potassium to total exchangeable bases (Ks/Cas+Mgs) in the soil

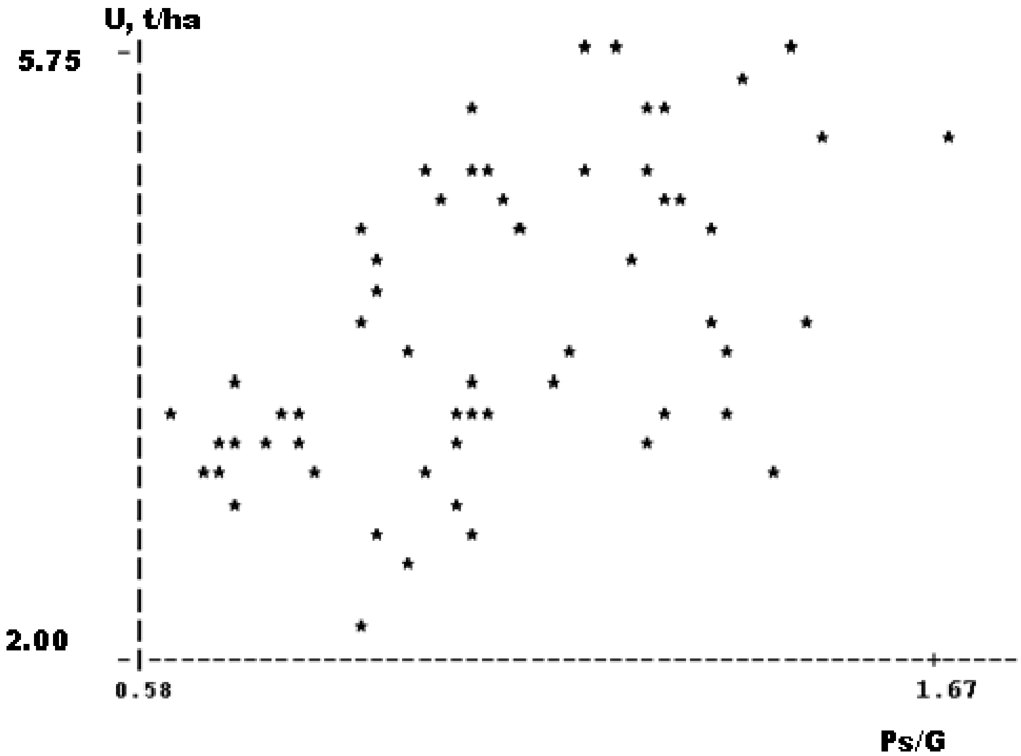

Fig. 2. Yield of winter wheat grain (U, t/ha) as a function of the ratio of available phosphorus to humus (Ps/G) in the plow soil layer

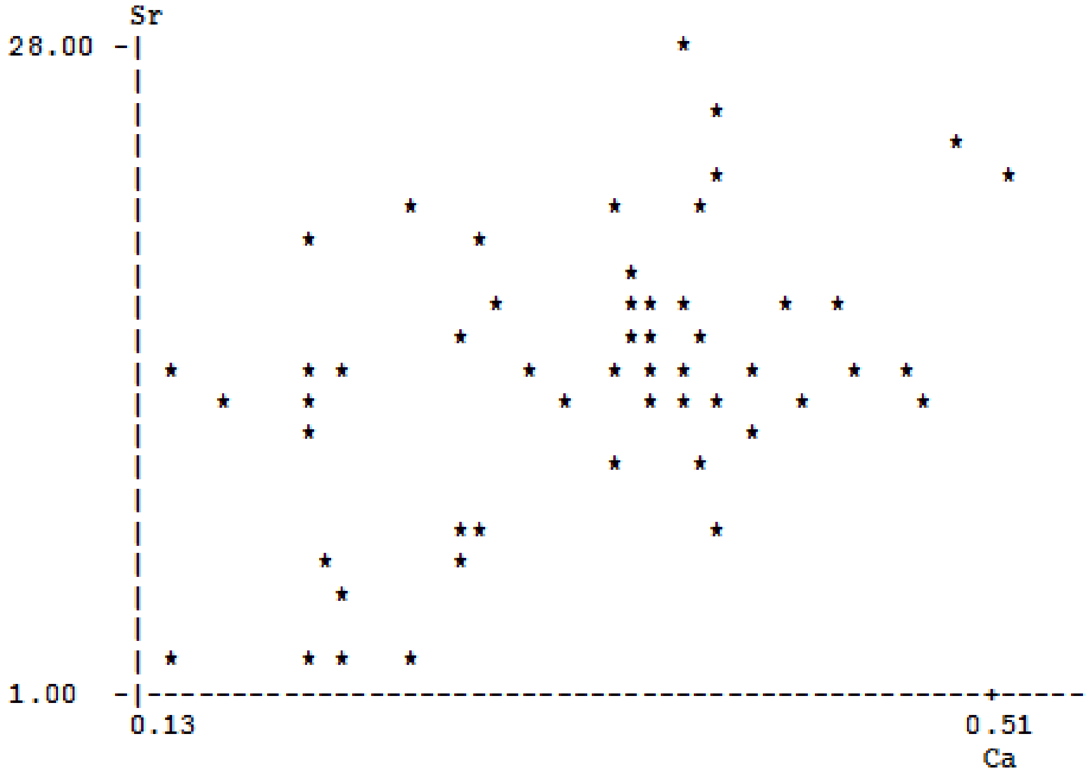

Fig. 3. Changes in the contents of strontium (Sr, mg/kg) and calcium (Ca, %) in the aboveground wheat biomass at the shooting stage

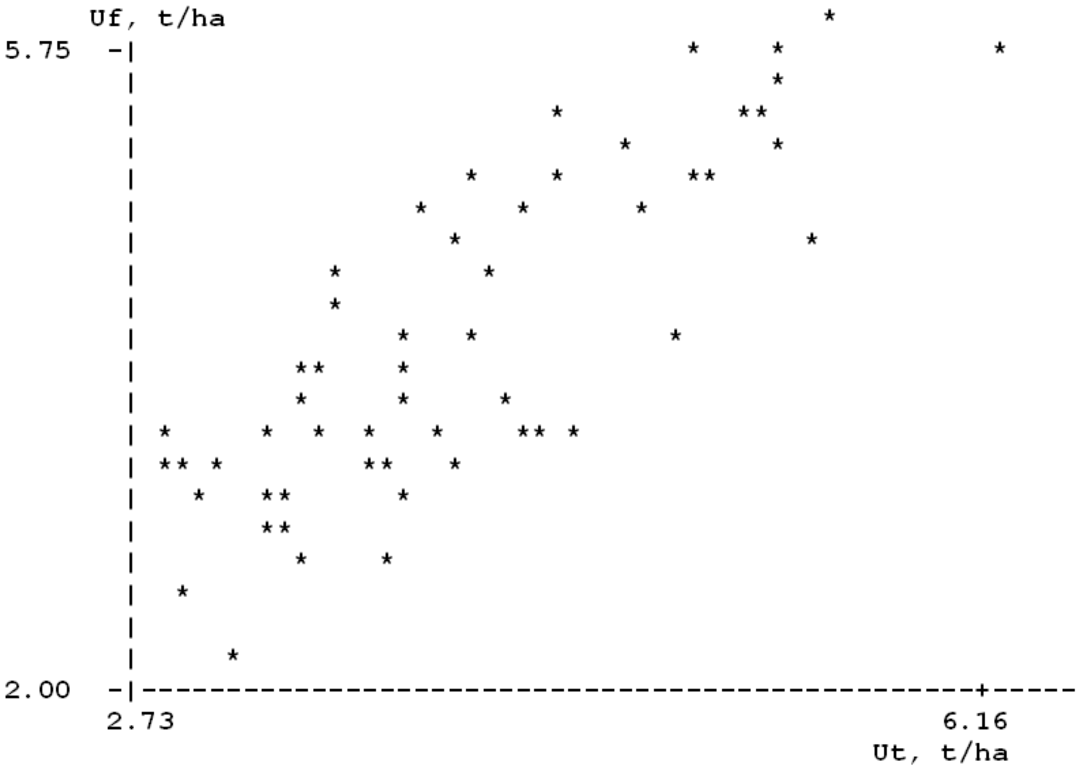

Fig. 4. Correlation between the factual (Uf) and predicted (Ut) yields of winter wheat grain

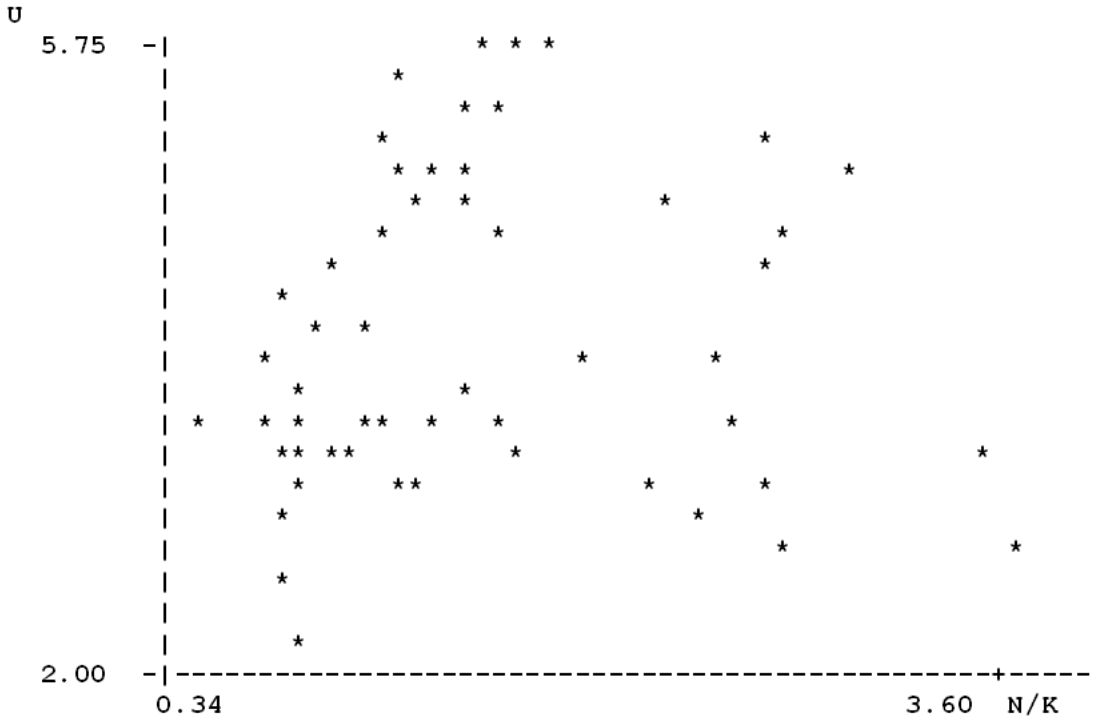

Fig. 5. Yield of winter wheat grain (U, t/ha) as a function of nitrogen/potassium (N/K) ratio in the aboveground plant biomass at the shooting stage

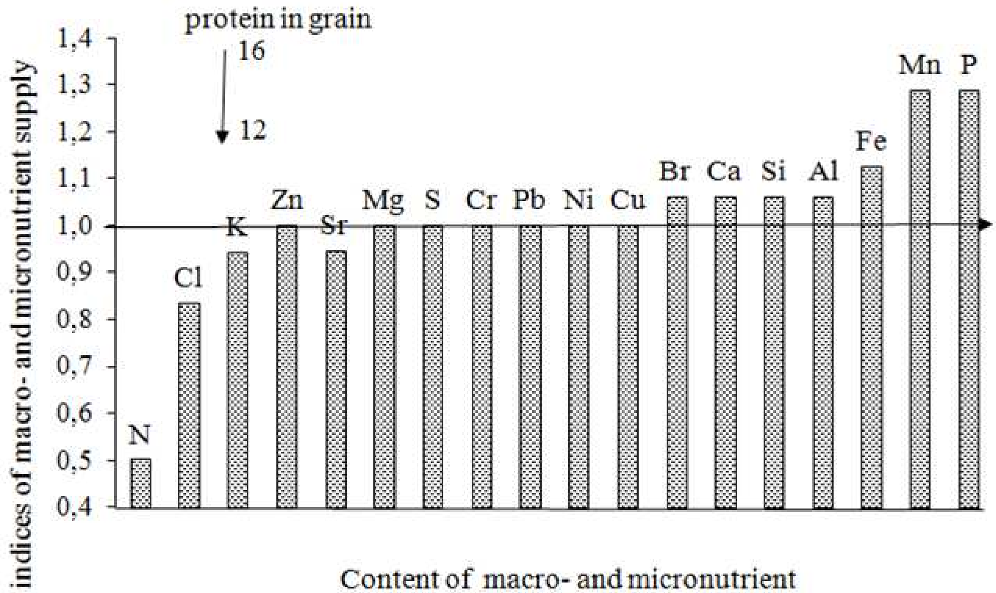

Fig. 6. Changes in the content of protein in winter wheat grain depending on the indices of macro- and micronutrient supply

The mean values of indicator parameters at which a winter wheat grain yield of 50 dt/ha is predicted are given in Table 3. This yield can be considered maximum at the growing of wheat on the unirrigated soils in the southern Russia. Therefore, these parameters can be considered optimum and used as criteria for the integrated assessment of the optimality of soil conditions.

The studies showed that the content of protein in winter wheat grain primarily depends on the deficit of nitrogen and its balance with Fe, P and Mn (Fig. 6).

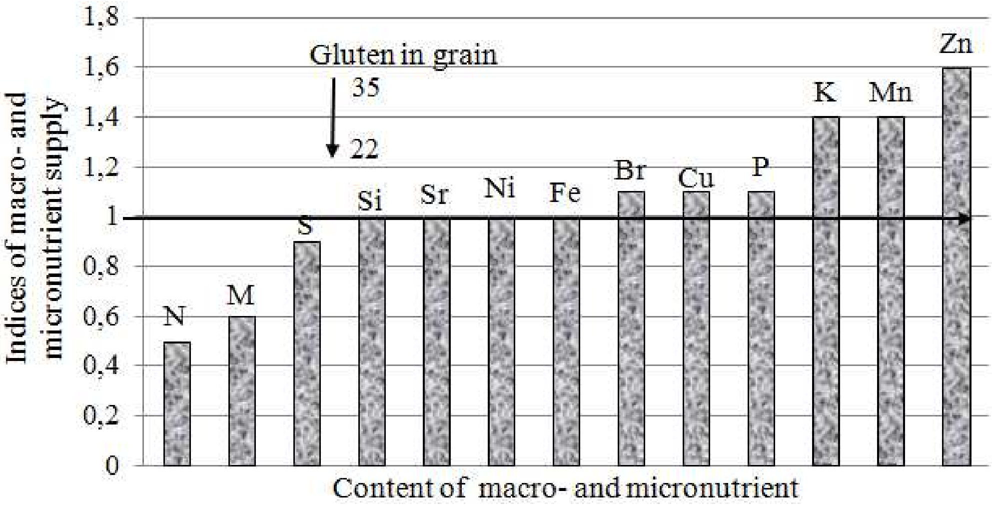

Fig. 7. Correlation of changes in the content of gluten in wheat grain with the availability indices of macro- and microelements

Table 1. Spatial variation of the calcareous chernozem fertility parameters and the winter wheat productivity in the production plantations

Agrochemical parameters of calcareous chernozem		Contents and ratios of chemical elements in the above-ground biomass of winter wheat		Parameters of planters ponseto the growing conditions	
Parameter	Minimum-maximum	Parameter	Minimum-maximum	Parameter	Minimum-maximum
G	2.7-4.4	N/Si	0.7-8.0	U	2.0-5.8
Ps	22.0-58.0	P	0.2-1.2	H1	45.0-90.0
Ks	240.0-460.0	K	1.0-4.0	M1	10.0-30.0
Cas	28.0-35.0	N/P	5.0-15.0	M2	2.0-6.0
Mgs	4.0-6.5	N/K	0.3-3.6	Prot	11.0-16.0
pH	7.0-7.8	K/P	2.0-16.0	Gl	22.0-35.0
Ks/Cas	0.7-2.2	Fe/Zn	4.0-56.0	Hard	45.0-72.0
Cas/Mgs	5.0-8.4	Sr	5.0-54.0		
Cas+Mgs	32.0-40.0	Mn	40.0-128.0		
Ps/G	0.5-1.7	Zn	5.0-31.0		
Ks/Cas	0.7-2.2	Ca	0.14-0.6		
Ks/Mgs	4.0-15.0	Si	0.4-1.8		
Ps/Mgs	0.4-1.4	N	1.2-3.4		

Note (hereandbelow): U is the yield ofwinterwheatgrain, t/ha; H1 is the plant height attheshootingstage, cm; M1, M2 arethegreenmassoftheplant at the shooting stage and the dry mass of the plant at the full ripeness stage, respectively, g; Prot, Gl, Hardare protein, gluten, and grain hardness, respectively, %; the contents of N, P, K, Si, and Caare given in %; the contents ofMn, Zn, Fe, and Srare given in mg/kg; N/P, N/K, K/P, Fe/Zn, N/Siare the ratios of the elements. Agrochemical parameters in the plow layer of soil:Gis the content of humus, %; Ks andPsdenote exchangeable potassium (K_2O) and available phosphorus (P_2O_5), respectively, mg/kg soil; Cas, Mgs are exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}), mmol(+)/100 g soil; Ks/Cas, Ps/G, Cas/Mgs, Ks/Cas+Mgsare the ratios between the above soil properties

The antagonism of these elements with N in plants can result in the deficit of Mn, P and Fe. This can decrease the content of protein in grain. Although the deficit of Mn does not hinder the synthesis of amino acids, its lack hampers their use for the synthesis of proteins (Gritsenko, 1974; Feng *et al*., 2014). Under conditions of Mn deficit, the photosynthesis is disturbed and gives insufficient contents of carbohydrates, which are considered among the key factors limiting the growth of roots (El'nikov *et al*., 2011). The data about the effect of the agrochemical properties of soils and the biometric parameters and chemical composition of plants at the shooting stage on the content of gluten were also analyzed (Mineev *et al*., 1981; Ames *et al*., 2003). This allowed revealing the system of indicators for the early prognosis of the essential quality parameters of winter wheat grain. The system of indicators for predicting the content of protein in the grain of winter wheat grown on calcareous chernozem includes 19 indicators. In the soil, these are the contents of available phosphorus and exchangeable potassium and their ratio, as well as the phosphorus to humus ratio.

Table 2. Wheat productivity predicted from the mathematical model as a function of soil agrochemical parameters and their ratios in production plantations

Agrochemical parameter and its mean value	Productivity	UtH1	Prot	Agrochemical parameter and its mean value	Productivity	UtH1
G				Ks/Cas+Mgs		
2.8	38.0	69	13	0.7	3.76	70.9
3.6	34.0	62	14	0.9	3.83	69.5
3.8	37.0	67	13	1,1	4.1	72.4
4	42.0	76	15	1.2	4.32	76.6
4.3	46.0	81	14	1.3	4.33	83.3
Ks				1.5	3.42	54
26.6	37.1	70.6	13.9	1.6	3.43	58.6
32.7	42.0	72.6	14.5	Cas/Mgs		
36.4	34.3	66	13.9	5.1	3.46	62.3
40.4	42.5	77	14.3	5.8	3.78	65.2
47.4	48.0	83	15.1	6.1	3.81	64
58	33.3	54	13.8	6.6	4	73
64	34.3	62.6	3.7	7	3.91	71
				7.4	4.08	77
Ks/Cas				7.8	3.85	71..0
0.8	37.6	70	14	8.4	4	67
1	38.6	71	14	pH		
1.2	39.4	69	14.4	7	3.98	74
1.3	44.1	89	14.5	7.1	4.22	73
1.6	43.1	81	14.8	7.2	5.17	83
1.9	35.5	54	13.8	7.3	3.89	69
2.1	32.3	62	14	7.4	4	72
Ps/G				7.5	3.71	72
0.6	32.7	65	13.6	7.6	3.69	70
0.8	32.0	61	13.7	7.8	3.2	55
0.9	36.0	53	13.9	Ps		
1	39.4	74	14.2	2.4	3.35	65.6
1.2	44.9	81	14.6	2.9	3.16	59.8
1.3	44.8	80	14.8	3.4	3.52	62.5
1.5	41.4	73	14.6	3.7	3.72	65.5
				4.1	4.2	80
				4.6	3.98	77
				5	4.53	82

Note: Ut is the yield of winter wheat grain predicted from model 1, t/ha

Table 3. Assessment criteria of the growing conditions of winter wheat on calcareous chernozem

Chemical elements and the irratiosin plants		Physicochemical properties of soil and biometric parameters of plants	
	%:	G	4.3
N	3	Ps (P_2O_5)	4
Si	0.8	Ks (K_2O)	40
P	0.3	Ks/Cas	1.3
K	2	Cas/Mgs	7.1
	mg/kgd.m.:	Cas+Mgs	36
Mn	70	pH	7.1
Fe	180		
Ni	2	plants, см	81
Cu	7		
	ratios		
		green mass of one plant, g	20
Fe/Mn	2.4		
N/K	1.2		
K/P	8.3		

The indicator elements in plants are N, Cl, K, P and Ca (%); Mn, Fe and Zn (mg/kg); the N/P, N/K, Mn/N, Fe/Zn and N/Ca ratios; and the weight of one plant (g). The early monitoring of wheat plantations for the content of protein can be performed using the following model 3.

This model best reflects the agrochemical features of calcareous chernozem. In a year with favorable climatic conditions, the content of protein in the grain of winter wheat grown on the soil highly supplied with available phosphorus can be predicted from only two parameters (model (4)).

The obtained data indicate that the intrafield variation in the content of raw gluten in the grain of winter wheat grown on calcareous chernozem is not chaotic; it is largely determined by the spatial heterogeneity of soil conditions affecting the plant supply with nitrogen and its balance with K, Mn, Zn and P (Fig. 7). This is also confirmed by the above linear regression model (5). However, in spite of the statistical significance of the model, the determination coefficient is low, which is related to the incomplete set of factors affecting the accumulation of raw gluten in grain included in the regression model.

For the agroecological assessment of soil suitability for different crops, it should be known what disturbances in plant nutrition at different development stages are correlated with the contents of chemical elements in grain and what of them are of special environmental hazard under the studied conditions. The contents of chemical elements in winter wheat grain depend on the quality of plant nutrition at the shooting stage, as confirmed by correlation analysis (in the first row, chemical elements in grain; in the second and third rows, elements and their ratios in the aboveground wheat biomass correlated with the elements from the first row):

Cu	Mn	Br	Zn	Ca	K	P	Pb	Sr	Sr/Ca	Ca/P
Sr	Si	N	N		Sr			Sr		N
Ni/Sr	Mn/Sr	N/Si	Si/Cl	N/K	Ca/Sr	N/K	Mn/Sr		Mn/Sr	Cu/Mg

The correlation coefficients are statistically significant at the probability level no less than 95% but low in value (0.4-0.6). However, the fact of this correlation indicates that the chemical composition of plants can be used for predicting the environmentally safe winter wheat grain. On calcareous chernozem, it is especially important to control the ratios of calcium to other elements in crop. The environmental stress in separate areas is assessed from the distortions in the Ca/P and Ca/Sr ratios in plant cuttings and fodders (Ermakov *et al*., 1993), which confirms the importance of using these criteria for the environmental assessment of crop quality and anthropogenic impacts on the soil. According to our data, the content of Sr in the aboveground plant biomass at the shooting stage reliably correlates with its content in winter wheat grain. The increase in the content of Sr in grain is accompanied by an unbalanced change in the contents of Ca and other elements, which can result in environmentally hazardous distortions of their ratios at different levels of gluten and protein. This indicates the importance of the development of plant diagnostic methods to predict the contents of strontium and calcium in winter wheat grain for the integral assessment of grain quality and soil conditions.

Conclusion

Long-term studies showed that calcareous chernozem is characterized by the high variation of agrochemical parameters (humus, available phosphorus, exchangeable potassium, pH, etc.). The variation of these parameters enhances the imbalance of plant nutrition with many macro- and micronutrients affecting the yield, quality and environmental safety of crops.

It was found that winter wheat strongly responses to the variation of nutrition quality. Reliable correlations were found between the crop yield and the contents of chemical elements and their ratios, which allow predicting the productivity of plants at the early development stage and assessing the fertility of soils on the basis of the environmentally significant ratios of chemical elements (P/Ca, Fe/Mn, Sr/Ca, etc.).

The following parameters are efficient indicators of the growing conditions of winter wheat on calcareous chernozem: The contents N, P, K, Fe, Zn and Ca and their ratios in the above-ground wheat biomass at the shooting stage; the contents of humus and available phosphorus and their ratio; and the content of exchangeable potassium and its ratios to exchangeable calcium and total exchangeable bases. It was shown that the prediction and integrated assessment of the grain quality of wheat grown on calcareous chernozem should be performed with consideration for the balance of macro- and micronutrients in wheat grain, the above-ground plant biomass at the shooting stage and the ratios of soil properties. It was found that the contents of protein and gluten in the grain of winter wheat grown on calcareous chernozem largely depend on the balance of N with Mn, P, Fe, Zn and K in plants at the shooting stage and the ratio between exchangeable potassium and humus in the soil.

The use of the integrated diagnostic system of plant nutrition expands opportunities for predicting the yield and grain quality of winter wheat grown on calcareous chernozem.

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Author's Contributions

This study is a result of the full collaboration of all authors.

Olga A. Biryukova: Interpreted the model and prepared the manuscript with contributions from all co-authors.

Bozhkov Dmitry Vasil'yevich: Participated in all experiments and coordinated the data-analysis.

Tatiana M. Minkina: Proposed the idea of ion's association in soil solution, system of equations.

Anna M. Medvedeva: Carried out the experiment.

Ivan I. Elnikov: Developed the mathematical model.

Ethics

The authors have not conflicts of interest in the development and publication of current research.

References

Ames, N.P., J.M. Clarke, J.E. Dexter, S.M. Woods and F. Selles *et al*., 2003. Effects of nitrogen fertilizer on protein quantity and gluten strength parameters in durum wheat (*Triticum turgidum* L. var. *durum*) Cultivars of variable gluten strength. Cer. Chem., 80: 203-211. DOI: 10.1094/CCHEM.2003.80.2.203

Anderson, N.P., J.M. Hart, N.W. Christensen, M.E. Mellbye and M.D. Flowers, 2010. Using the nitrogen mineralization soil test to predict spring fertilizer n rate for soft white winter wheat grown in western Oregon. Oregon State University.

Bereza, O.V., A.I. Strashnaya and E.A. Lupyan, 2015. On the possibility to predict the yield of winter wheat in the Middle Volga region on the basis of integration of land and satellite data. Sovremennye Problemy Distantsionnogo Zondirovaniya Zemliiz Kosmosa, 12: 18-30.

Biryukova, O.A., M.F. Lanina and I.I. Lanin, 2005. Diagnostics of the grain quality of winter wheat grown on calcareous ordinary chernozem. Rostov State University, Rostizdat, Rostov-on-Don.

El'nikov, I.I. and A.N. Prokhorov, 1989. Methodological recommendations on the regulation of macro- and micronutrient ratios in plants according to the ISOD system. RASKhN, Moscow.

El'nikov, I.I. and E.N. Savvinova, 2006. Effective fertility of agrosoddy-podzolic soils under the long-term aftereffect of mineral and organic fertilizers. Moscow.

El'nikov, I.I. and O.A. Biryukova, 2011. Diagnostics of grain quality of winter wheat grown on calcareous chernozem. ProblemyAlgrokhimii i Agroekologii, 4: 20-24.

El'nikov, I.I., 2002. Mineral Nutrition Balance in Plants on Different Soils. In: Soils of Moscow Region and Their Use, L.L. Shishov and N.V. Voitovich (Eds.), pp: 439-481.

Ermakov, V.V., V.N. Bashkin and V.V. Snakin, 1993. Biogeochemical criteria for the evaluation of ecological state of landscapes. Biogeochemical Fundamentals of Ecological Standards, Nauka, St. Petersburg.

Feng, M.C., L.J. Xiao, M.J. Zhang, W.D. Yang and G.W. Ding, 2014. Integrating remote sensing and GIS for prediction of winter wheat (*Triticum aestivum*) protein contents in Linfen (Shanxi), China. PLoS One, 9: 1-10. PMID: 24404124

GOST 10846, 1991. Interstate standard. Grain and products of its processing. Methods of Determination of Protein, Moscow.

GOST 13586.1, 1968. Interstate Standard. Grain, Methods of Determination Quantity and Quality of Gluten in Wheat, Moscow.

Gritsenko, A.A., 1974. Effect of fertilizers and weather on the content of protein in Bezostaya 1 winter wheat. Agrokhimiya, 10: 50-54.

Hasegawaa, H. and R.F. Denison, 2006. Model predictions of winter rainfall effects on N dynamics of winter wheat rotation following legume cover crop or fallow. Int. J. Rem., 27: 737-175. DOI: 10.1016/j.fcr.2004.07.019

Kildyushkin, V.M., Y.V. Khomutv, V.A. Kornev and V.G. Prokopets, 2010. Effect of weather and climate factors on winter wheat yield. Dostizheniya Nauki i Tekhniki, 2: 26-28.

Kochetkova, O.V., D.A. Ospishchev and N.V. Shevchenko, 2014. System-cognitive model and the procedure of its application for predicting the yield of winter wheat. Izvestiya Nizhnevolzhskogo Agrouniversitetskogo Kompleksa, 4: 1-5.

Kogan, F., G. Menzhulin, N. Shamshurina and A. Pavlovsky, 2011. New Regression Models for Prediction of Grain Yield Anomalies from Satellite-Based Vegetation Health Indices. In: Use of Satellite and In-situ Data to Improve Sustainability, Kogan, F., A. Powell and O. Fedorov, (Eds.), Springer, Dordrecht, ISBN-10: 9048196183, pp: 105-112.

Kogan, F., N.N. Kossul, T.I. Adamenko, S.V. Skakun and A.N. Kravchenko *et al*., 2013. Comparative analysis of regression and biophysical models in predicting the yield of winter wheat. Sovremennye Problemy Distantsionnogo Zondirovaniya Zemliiz Kosmosa, 10: 215-227.

Kolotii, A.V., 2012. Regression models for predicting the yield of winter wheat in Ukraine. Induktivne Modelyuvannya Skladnikh Syst., 4: 92-101.

Kussul, N., S. Skakun, A. Shelestov, O. Kravchenko and J. Gallego *et al*., 2012. Crop area estimation in Ukraine using satellite data within the MARS project. Proceedings of the IEEE International Geoscience and Remote Sensing Symposium, Jul. 22-27, IEEE Xplore Press, Munich, pp: 3756-3759. DOI: 10.1109/IGARSS.2012.6350500

Liu, L., J. Wang, Y. Bao, W. Huang and Z. Ma *et al*., 2006. Predicting winter wheat condition, grain yield and protein content using multi-temporal EnviSat-ASAR and Landsat TM satellite images. Int. J. Rem. Sens., 27: 737-753. DOI: 10.1080/01431160500296867

Mansouri, M., B. Dumont and M.F. Destain, 2014. Bayesian methods for predicting and modelling winter wheat biomass. ULg Library Network.

Marenich, N.N. and V.S. Shkurko, 2014. Effect of meteorological factors on the yield of cereal crops and possibility of yield prediction. Vestnik Kurganskoi GSKhA, 1: 18-20.

Mineev, V.G. and A.N. Pavlov, 1981. Agrochemical principles of increasing the wheat grain quality. Kolos, Moscow.

Mineev, V.G., 2001. Laboratory manual on agricultural chemistry. MGU, Moscow.

Mineev, V.G., 2005. Selected works. MGU, Moscow.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone and E.V. Lukina *et al*., 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93: 131-138. DOI: 10.2134/agronj2001.931131x

Ryabchun, N.I., 2014. Prediction of soft winter wheat yield at different stages of development. Zernobobovye i Krupyanye Kul'tury, 1: 91-99.

Schillinger, W.F., S.E. Schofstoll and J.R. Alldredge, 2012. Predicting wheat grain yields based on available water. Washington State University Extension.

Spiertz, H., 2013. Challenges for crop production research in improving land use, productivity and sustainability. Sustainability, 5: 1632-1644. DOI: 10.3390/su5041632

Vinogradov, D.Y., 2014. Effect of agricultural practices on the yield of winter wheat and its prediction under different weather conditions of the Central Chernozemic Zone.

Ziganshin, A.A. and L.R. Sharifullin, 1974. Factors of Planned Crop Yields, Kazan.

Zinchenko, V.E., 2005. Predicting the yield of winter crops and the response of spring barley and winter wheat to different tillage methods of solonetzes in Rostov oblast.