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ЗАВИСИМОСТЬ АГРОХИМИЧЕСКИХ И АГРОФИЗИЧЕСКИХ СВОЙСТВ ВЫЩЕЛОЧЕННОГО ЧЕРНОЗЕМА ОТ СИСТЕМЫ ОБРАБОТКИ ПОЧВЫ

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Представлены результаты исследований по изучению зависимости агрохимических и агрофизических свойств выщелоченного чернозема от системы обработки почвы. Работа выполнена в 2015–2019 гг. в длительном стационарном полевом опыте в посевах яровой мягкой пшеницы Сибирский Альянс. Почва опытного участка – чернозем выщелоченный среднемощный среднегумусный тяжелосуглинистый. Предшественниками пшеницы были чистый пар, сидеральный пар (рапс), сидеральный пар (донник). Изучены следующие системы обработки почвы: отвальная глубокая (контроль), комбинированная глубокая, комбинированная минимальная, отвальная минимальная. Отмечено преимущество по содержанию нитратного азота в почве до посева, в фазу кущения и колошения пшеницы по предшественнику сидеральный пар (рапс) при использовании отвальной минимальной системы обработки (осенью заделка сидеральной культуры БДТ-3). Установлено влияние системы обработки на содержание нитратного азота в почве в фазу кущения пшеницы – 15,5%, условий года – 12,9, взаимодействия данных факторов – 20,1%. Выявлена положительная взаимосвязь между содержанием нитратного азота в почве и количеством подвижного фосфора по предшественнику сидеральный пар (рапс), r = 0,7118–0,8917 (R = 0,9500). Высокие показатели содержания P_2O_5 (от 150 мг/кг и выше) отмечены в среднем за 5 лет в фазу колошения пшеницы – от 145,0 до 165,6 мг/кг. Максимальные значения P_2O_5 выявлены по сидеральному пару (рапс) при комбинированной минимальной и отвальной минимальной системах обработки почвы. Достоверное превышение содержания обменного калия в сравнении с контролем по средним показателям за 2015–2019 гг. отмечено при комбинированной глубокой системе обработки – 5,0 мг/кг ($НСР_{05}$). При остальных изучаемых системах обработки показатели находились на уровне контроля. Выявлены более высокие коэффициенты структурности при отвальной глубокой системе обработки (контроль) – 2,54, комбинированной минимальной – 2,47, отвальной минимальной – 2,23 по предшественнику сидеральный пар (рапс); по сидеральному пару (донник) – 2,98 (отвальная глубокая). При увеличении коэффициента структурности отмечено снижение показателя плотности сложения почвы, r = –0,3499 (R = 0,5760). Выявлена тенденция к снижению плотности сложения почвы до 0,98 г/см^3 по предшественнику сидеральный пар (рапс) при минимализации обработки почвы: комбинированной отвальной и минимальной отвальной; при отвальной глубокой (контроль) – 1,02 г/см^3. В результате корреляционного анализа установлено, что при увеличении плотности сложения почвы снижается содержание P_2O_5, r = –0,4898, K_2O, r = –0,2530.

Ключевые слова: яровая мягкая пшеница, система обработки почвы, предшественник, агрофизические свойства почвы, водопрочные макроагрегаты, плотность почвы, агрохимические свойства почвы

DEPENDENCE OF AGROCHEMICAL AND AGROPHYSICAL PROPERTIES OF LEACHED CHERNOZEM ON SOIL TREATMENT SYSTEM

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The results of research on the dependence of agrochemical and agrophysical properties of leached chernozem on the system of soil treatment are presented. The work was performed in 2015–2019 in a long-term stationary field experiment in crops of spring soft wheat Siberian Alliance. The soil of the experimental site is medium-powered medium-humus heavy-loamy leached chernozem. Wheat was preceded by clean fallow, green fallow (rape), green fallow (cloverleaf). The following tillage systems were studied: deep moldboard (control), deep combined, minimum combined, minimum moldboard. There is an advantage in nitrate nitrogen content in the soil before sowing, in the phase of tillering and earing of wheat on the preceding cereal fallow (rape) when using the minimum tillage system (in autumn the break crop BDT-3 is planted). The effect of the tillage system on the nitrate nitrogen content in the soil in the phase of bushing of wheat - 15,5%, conditions of the year - 12,9, the interaction of these factors - 20,1% was determined. A positive relationship between the content of nitrate nitrogen in the soil and the amount of mobile phosphorus on the precursor green fallow (rape), r = 0.7118-0.8917 (R = 0.9500), was detected. High P_2O_5 content (from 150 mg/kg and above) was recorded on average for 5 years during the earing phase of wheat - 145.0 to 165.6 mg/kg. Maximum P_2O_5 values were detected for green fallow (rape) under minimum combined and minimum moldboard systems. A significant increase in exchangeable potassium content over the control average for 2015-2019 was observed with the deep combined tillage system - 5.0 mg/kg (NSR_{05}). With the other tillage systems studied, the figures were at the control level. Higher soil pedality coefficients were revealed with a deep moldboard processing system (control) - 2.54, a minimum combined - 2.47, a minimum moldboard - 2.23 according to the predecessor green fallow (rapeseed); for green fallow (melilot) - 2.98 (deep moldboard). With an increase in the pedality coefficient, there was a decrease in the soil bulk density index, r = -0.3499 (R = 0.5760). A tendency was revealed towards a decrease in the soil bulk density to 0.98 g/cm^3 according to the predecessor green fallow (rapeseed) with minimization of soil cultivation: combined moldboard and minimum moldboard; with a deep moldboard (control) - 1.02 g / cm^3. As a result of the correlation analysis, it was found that with an increase in the soil bulk density, the content of P_2O_5, r = –0.4898, K_2O, r = –0.2530, decreases.

Keywords: spring soft wheat, soil tillage system, predecessor, soil agrophysical properties, waterproof macroaggregates, soil density, soil agrochemical properties

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INTRODUCTION

Agrochemical soil properties determine soil fertility [1,2].

Mineral nutrition is one of the main regulated factors used to target plant growth and development. A prerequisite for high crop productivity is an optimally balanced plant nutrition system [1–3].

During the mineralization of soil organic matter, nitrogen is mobilized through absorption by microflora and binding of ammonia [4, 5]. Nitrogen is one of the elements whose compounds play an enormous role in biomass creation, natural and anthropogenic systems functioning [6–8]. Optimization of mineral nutrition is closely linked to nitrogen uptake, transport and metabolism, which determines the size and quality of the crop. With sufficient nitrogen intake from the soil, plants accumulate considerable biomass during the tillering phase, when the numerical side of the crop is established during the 4th-5th stages of organogenesis in cereal crops (number of spikelets and flowers in the spike) [9].

Wheat experiences phosphorus deficiencies earlier than nitrogen deficiencies. It responds to additional phosphorus fertilization even before the tillering phase. If wheat is supplied with phosphorus before earing, its yield is not reduced even if no phosphorus fertilizer is applied in later phases[3].

The content of mobile forms of phosphorus and potassium is one of the most important agrochemical indicators of soil fertility. A good phosphorus supply improves carbohydrate metabolism, leads to the accumulation of sugars, which contributes to frost and winter hardiness, ensures economical use of moisture and increases drought tolerance of plants. A lack of available phosphorus slows down protein synthesis and increases nitrate nitrogen in plant tissues [10–12].

Optimum potassium availability in arable soils is one of the prerequisites for high crop productivity and sustainable agroecosystems [13, 14].

P.A. Chekmarev and P.V. Prudnikov, considering the role of potassium in farming, explain that fundamental, physiological-biochemical and ecological studies not only confirm the known, but also discover new functions of this element: it enhances the process of photosynthesis and assimilation of CO_2, promotes a greater accumulation of assimilants in the spare organs of plants [15].

Tillage in the farming system is regarded by many scientists as a powerful factor influencing its agrochemical and agrophysical properties. There are many examples of the effectiveness of minimum tillage systems and direct sowing in Russia. In the Novosibirsk region, the Rubin and Novomayskoye farms in Krasnozersky district and the Stepnoye farm in Iskitimsky district use the direct sowing technology on tens of thousands of hectares and produce high and stable yields annually [16].

Academician V.I. Kiryushin made a major contribution to the study of tillage methods and systems at different levels of intensification. Under his leadership at the Siberian Research Institute of Farming, stationary multifactorial experiments were set up in practically all soil and climate zones of the Novosibirsk Region[4].

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[4]Kiryushin V.I. Methodological concept of agricultural development in Siberia: Methodological recommendations. Novosibirsk, 1989. 45 p.

Generalization of the results of the conducted experiments has shown that under optimization of mineral nutrition of plants and phytosanitary situation the yield capacity of grain crops at different tillage from deep tillage to zero tillage on different types of soil (southern heavy loamy chernozem, ordinary heavy loamy chernozem, leached heavy loamy chernozem, meadow-chernozem soil) was not different[5].

The mechanical factors of structure formation are particularly strong during tillage. Tillage implements produce the greatest amount of macro-aggregate when the soil is physically ripe [17].

The purpose of the research is to study the dependence of agrochemical and agrophysical properties of leached chernozem on the tillage system.

MATERIAL AND METHODS

The work was carried out in a long-term stationary field experiment at the Kemerovo Research Institute of Agriculture, a branch of the Siberian Federal Research Centre of AgroBioTechnologies of the Russian Academy of Sciences.

The soil of the experimental plot is medium-powered medium-humus heavy-loamy leached chernozem with a humus content of 8.2% in the arable layer. The research was carried out in a four-field cereal fallow rotation (fallow - wheat - pea - barley) using the following tillage systems: mouldboard deep, combined deep, combined minimum, mouldboard minimum.

Tillage systems:

– mouldboard deep: annual main tillage for all crops - ploughing with plough PN-4-35 to a depth of 25-27 cm, spring moisture closure with BZT-1, C-11, pre-sowing cultivation with AKP "Leader-2,1";

– combined deep: annually for all crops shallow tillage to a depth of 25-27 cm with the KPG-250 subsurface cultivator, in spring moisture closure with BZT-1, C-11, pre-sowing cultivation with KPS-4,2;

– combined minimum: annually under all crops shallow main tillage to a depth of 12-14 cm with the KPG-250 subsurface cultivator, in spring moisture closure with BZT-1, C-11, pre-sowing cultivation with KPE-3,8;

– mouldboard minimum: annually, on forecrops, complete and green manure fallow autumn processing BDT-3, in spring direct sowing with a sowing complex.

Sowing in all variants was carried out with the Tom-5.1 seeding complex with a simultaneous application of 1.0 c/ha of ammophos ($N_{12}P_{52}$). Experimental plot area by tillage was 4720 m^2, record area - 100 m^2, four times repetition. The spring wheat variety Siberian Alliance was sown on three different predecessors: complete fallow, green fallow (rapeseed) and green fallow (melilot).

Soil moisture was determined by thermostatic weight method in a meter layer according to spring barley development phases[6], agrophysical properties of soil - according to N.A. Kachinsky method[7], bulk density or density volume (dv) - as the mass of absolutely dry soil (M) in the unit of soil volume (V) with all natural soil voids (g/cm^3) (dv = M/V). The density of the soil was set by layer, then calculated for a layer of 40 cm. The aggregate composition of the soil was determined by the method of N.I. Savvinov, which is based on the possibility of dividing the soil into fractions on sieves with holes of different diameters (see footnote 7).

Grain harvesting was carried out by solid harvesting using a Sampo-130 plot harvester. Grain yield figures are given for 100% purity and 14% moisture content according to GOST 13586.5-9368. Statistical processing of the obtained data was carried out by the method of analysis of variance according to B.A. Dospekhov[9] using computer programs of O.D. Sorokin[10].

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RESULTS AND DISCUSSION

Over the years of the study (2015-2019), the nitrate nitrogen content in spring soft wheat crops varied during the growing season (see Table 1). The specific behavior of nitrate nitrogen in the soil is such that its presence should be monitored annually before sowing. Nitrate nitrogen is in the soil solution, so its fluctuations in the arable layer during the growing season are significantly influenced by moisture conditions [18].

Over the years of the surveys, the average pre-sowing nitrate nitrogen content was 13.6 mg/kg soil in 2015, 2016 - 10.0, 2017- 21.8, 2018 - 12.0, 2019 - 11.9 mg/kg. The proportion of the influence of the conditions of the year on the nitrate nitrogen content before sowing - 48.6%, tillage system - 7.7% was detected.

Prior to sowing, $N\text{-}NO_3$ content averaged 10.6-17.5 mg/kg of soil in 5 years for the complete fallow preceding crop, with the advantage of minimum tillage systems - combined and mouldboard: 17.5 and 17.4 mg/kg of soil, respectively. This trend continues for the preceding green manure fallow (rapeseed) and green manure fallow (melilot). For rapeseed, a reliable advantage in $N\text{-}NO_3$ content was given by the minimum mouldboard tillage system, exceeding the control (deep tillage) by 2.1 mg/kg of soil (LSD_{05} = 1.83).

The content of nitrate nitrogen increased compared to the control for the forecrop with green manure fallow (melilot) at combined deep tillage by 2.1 mg/kg, combined minimum by 3.6 and mouldboard minimum tillage by 5.4 mg/kg.

The application of ammophos ($N_{12}P_{52}$) simultaneously with sowing and the nitrification processes in the soil increased the nitrate nitrogen content in the soil by the tillering phase of spring soft wheat. The highest content of $N\text{-}NO_3$ was noted for the forecrops of green manure fallow (melilot) and green manure fallow (rapeseed) when using the minimum tillage

Табл. 1. Содержание $N\text{-}NO_3$ в посевах яровой мягкой пшеницы Сибирский Альянс в слое почвы 0–40 см (2015–2019 гг.), мг/кг почвы

Table 1. The content of $N\text{-}NO_3$ in crops of spring soft wheat Siberian Alliance in the soil layer is 0-40 cm, mg/kg of soil (2015-2019)

Soil tillage system	Before sowing	Tillering phase	Earing phase
Complete fallow forecrop			
Deep mouldboard (control)	10,6	16,3	15,4
Deep combined	14,5	22,0	11,7
Minimum combined	17,5	22,2	14,3
Minimum mouldboard	17,4	21,8	14,9
Green manure fallow (rapeseed grass)			
Deep mouldboard (control)	12,5	19,9	14,5
Deep combined	13,7	20,6	14,5
Minimum combined	13,5	19,3	15,5
Minimum mouldboard	14,6	28,3	16,8
Green manure fallow (melilot)			
Deep mouldboard (control)	10,3	19,1	12,2
Deep combined	12,4	19,8	11,7
Minimum combined	13,9	21,7	13,6
Minimum mouldboard	15,7	27,9	11,9

Average by factors, $N\text{-}NO_3$, mg/kg of soil; tillage system: deep mouldboard - 14.5, deep combined - 15.7, minimum combined - 16.8, minimum mouldboard - 18.8; development phases: pre-sowing - 13.9, tillering phase - 21.6, earing phase - 13.9; forecrop: complete fallow - 16.5, green manure fallow (rape) - 17.0, green manure fallow (melilot) - 15.9; LSD_{05} by factors, mg/kg soil: tillage system - 1.83, forecrop - 1.59, development phases - 1.59.

system (in autumn the BDT-3 was embedded in the green manure fallow) - 27.9 and 28.3 mg/kg of soil, respectively.

Increased nitrate nitrogen content in the tillering phase was observed in 2015-2019 when combined deep and minimum tillage systems were used: for the forecrop complete fallow - 22.0-22.2 mg/kg soil, green manure fallow (rapeseed) - 20.6 and 19.3, green manure fallow (melilot) - 19.8 and 21.7 mg/kg respectively. In the mouldboard deep tillage system, the $N\text{-}NO_3$ content is 16.3-19.9 mg/kg of soil, depending on the predecessor. The effect of the tillage system on the nitrate nitrogen content in the soil during the tillering phase of spring soft wheat was 15.5%, the effect of the conditions of the year was 12.9, and the interaction of these factors was 20.1%.

The influence of the year's conditions was largely determined by moisture availability. A positive correlation has been established between the hydrothermal coefficient (HTC) during the vegetation period and the nitrate nitrogen content during the waxy maturity phase of spring soft wheat. For the complete fallow forecrop this correlation was observed in 2015-2018: r = 0.5315-0.9736* (* - hereafter in the text means above the confidence threshold), for rapeseed in 2017-2018 r = 0.3204-0.8690, for melilot in 2015-2016 r = 0.7313-0.9730*.

According to the 5-year averages (2015-2019), reliably high content of productive moisture in the soil layer 0-20 cm in the period of sowing was noted in the forecrops complete fallow and green manure fallow (rapeseed) at mouldboard minimum tillage - 29.7 mm, at mouldboard deep tillage (control) - 26.3 and 27.4 mm respectively (see Table 2).

According to the average values for 2015-2019 the highest content of productive moisture in the 0-20 cm layer of the soil was noted in the tillering phase for the forecrop green manure fallow (rapeseed) at mouldboard minimum tillage system (27,3 mm) compared to the control (mouldboard deep tillage, 22,7 mm), for the complete fallow forecrop at combined minimum - 25.4 mm (control - 20,2 mm). For complete fallow, the reserves of productive moisture in the minimum tillage system are higher by 3.2 mm compared to the control. For green manure fallow (melilot), stocks of productive moisture in all tillage systems are at the control level - 23.9-24.2 mm (control - 20.3 mm, LSD_{05} = 4.69). The results of the analysis of variance showed that the highest (21.3%) influence on the content of productive moisture in the root layer of the soil was caused by tillage systems, the influence of the forecrop was not established.

The annual precipitation in the phase of earing of spring wheat in the northern forest-steppe of the Kuznetsk Depression was noted. The content of productive moisture in the root layer of the soil on the average indicators for 2015-2019 is high enough for grain filling: 29.5 mm for complete fallow, 29.9 mm for green manure fallow (rapeseed), 31.0 mm for melilot. The influence of tillage system on the content of productive moisture in the tillering phase in the soil layer 0-100 cm - 4.6%, in the earing phase of this influence is not established.

The use of minimum technologies with the introduction of green crops and perennial grasses in the crop rotation, preservation of stubble backgrounds increases the biological activity of the soil in the rhizosphere, mineralization of organic matter with the release of available forms of nutrients, in particular nitrate nitrogen [19].

When spring soft wheat plants used nitrate nitrogen from heading stage to earing stage, its content decreased on average by 35.7% (from 21.6 to 13.9 mg/kg of soil). The effect of the tillage system on the nitrate nitrogen content in the soil during the earing phase was 10.7%, while the effect of the forecrop was not detected. The highest content of nitrate nitrogen was found in this phase with mouldboard minimum soil tillage system for rapeseed forecrop - 16.8 mg/kg of soil, control - 14.5 mg/kg.

The mobile forms of phosphorus practically do not move through the soil profile; therefore, its content in the root-containing soil layer (0-40 cm) is most important in assessing the availability of phosphorus in plants. Classification of soils in terms of the content of mobile phosphorus compounds in soils according to Chirikov is as follows: less than 20 mg/kg soil - very low content; 20 to 50 - low; 50 to 100 - medium;

Табл. 2. Запасы продуктивной влаги в посевах яровой мягкой пшеницы в слое почвы 0–20 см (2015–2019 гг.), мм

Table 2. Reserves of productive moisture in crops of spring soft wheat in the soil layer 0–20 cm (2015–2019), mm

Soil tillage system	Sowing	Tillering	Earing
Complete fallow forecrop			
Deep mouldboard (control)	26,3	20,2	27,7
Deep combined	25,8	21,4	31,1
Minimum combined	26,9	25,4	29,9
Minimum mouldboard	29,7	23,4	29,2
Green manure fallow (rapeseed grass)			
Deep mouldboard (control)	27,4	22,7	29,5
Deep combined	27,6	19,0	30,6
Minimum combined	27,7	21,3	30,8
Minimum mouldboard	29,7	27,3	28,8
Green manure fallow (melilot)			
Deep mouldboard (control)	24,8	20,3	30,4
Deep combined	25,5	23,9	30,5
Minimum combined	26,1	24,2	31,8
Minimum mouldboard	26,7	24,0	31,4

LSD_{05} by factors (sowing): tillage system - 2.0, forecrop - 1.74.
LSD_{05} by factors (tillering): tillage system - 4.69, forecrop - 4.06.
LSD_{05} by factors (earing): tillage system - 1.75, forecrop - 1.52.

100 to 150 - increased; 150 to 200 - high; over 200 mg/kg - very high [20].

The content of mobile phosphorus on average for 2015-2019 in the crops of spring soft wheat Siberian Alliance regardless of the forecrop is characterized as elevated: before sowing from 132.6 to 148.8 mg/kg soil, in the tillering phase from 137.4 to 150.0 mg/kg (see Table 3).

High P_2O_5 content (from 150 mg/kg and above) was recorded on average for 5 years during the earing phase, from 145.0 to 165.6 mg/kg. The maximum values were obtained for green manure fallow (rapeseed) with combined minimum soil tillage system - 160.6 mg/kg of soil - and mouldboard minimum - 165.6 mg/kg, with mouldboard deep (control) - 150.6 mg/kg. The share of the influence of the soil tillage system on the content of mobile phosphorus was 5.1% and that of the forecrop - 2.8%.

The high content of mobile phosphorus during earing stage - 161.6 mg/kg of soil (control - 151.0 mg/kg) was also observed with mouldboard minimum tillage system for the green manure fallow forecrop (melilot).

Correlation analysis based on our results showed a positive relationship between the content of nitrate nitrogen in the soil and the amount of mobile phosphorus on the forecrop of green manure fallow (rapeseed), r = 0.7118-0.8917 (R = 0.9500). In accordance with the increase of phosphorus availability, the microbiological activity of the soil increases and the content of nitrate nitrogen increases [21, 22].

The content of exchangeable potassium varied between the test variants. On average (2015-2019), the K2O content in mouldboard deep soil tillage system (control) was 107.8 mg/kg soil, combined deep tillage was 112.8, combined minimum tillage was 110.0, and mouldboard minimum tillage was 106.2 mg/kg (see Table 4).

A significant increase in the content of exchangeable potassium in comparison with the control was noted with the combined deep tillage system - 5.0 mg/kg (LSD_{05}), with the other

Табл. 3. Содержание P_2O_5 в посевах яровой мягкой пшеницы Сибирский Альянс в слое почвы 0–40 см по фазам развития растений (2015–2019 гг.), мг/кг почвы

Table 3. P_2O_5 content in spring soft wheat crops Siberian Alliance in soil layer 0–40 cm, mg/kg of soil, by plant development phases (2015–2019)

Soil tillage system	Before sowing	Tillering phase	Earing phase
Complete fallow forecrop			
Deep mouldboard (control)	132,6	137,4	154,8
Deep combined	140,0	143,0	152,4
Minimum combined	144,4	147,2	154,6
Minimum mouldboard	139,6	141,0	156,0
Green manure fallow (rapeseed grass)			
Deep mouldboard (control)	144,2	143,4	150,6
Deep combined	143,6	143,0	150,4
Minimum combined	147,0	147,6	160,6
Minimum mouldboard	139,8	147,2	165,6
Green manure fallow (melilot)			
Deep mouldboard (control)	148,8	149,2	151,0
Deep combined	141,6	142,4	145,0
Minimum combined	144,0	141,0	147,2
Minimum mouldboard	143,4	150,0	161,6

Average by factors, mg/kg of soil: P_2O_5, soil tillage system: mouldboard deep - -145.8, combined deep - 144.6, combined minimum - 148.2, mouldboard minimum - 149.4; development phases: pre-sowing - 142.4, tillering phase - 144.4, earing phase - 154.1; forecrop: complete fallow - 145.3, green manure fallow (rapeseed) - 148.6, green manure fallow (melilot) - 147.1; LSD_{05} by factors, mg/kg soil: tillage system - 3.23, forecrop -2.80, development phases - 2.80.

studied systems of cultivation indicators are at the control level. The influence of the tillage system on the exchangeable potassium content was 7.5%, that of the forecrop 18.5, and the interaction of these factors was 12.3%.

The content of exchangeable potassium increased during the vegetation period of spring soft wheat with the combined deep tillage system: by the forecrop complete fallow before sowing - 113.2 mg/kg, during tillering - 101.2, earing - 117.0 mg/kg, by the control - 108.8; 95.2; 106.2 mg/kg, respectively. The same tendency was found with the combined minimum tillage system: the excess to the control was 3.8-7.6 mg/kg of soil. For green manure fallow (rapeseed), the increase in exchangeable potassium content compared to the control was either absent or negligible under all tillage systems.

M.L. Tsvetkov and A.F. Kolesnikov note from their studies that the roots of melilot plants are able to assimilate hard-to-reach forms of plant mineral nutrients (potassium and phosphorus) from deep soil layers due to a well-developed root system. The content of mobile phosphorus and exchangeable potassium in the soil increases when sowing in the crop rotation on the preceding green manure fallow (melilot) [23].

According to the content of K_2O before sowing spring soft wheat on the green manure fallow (melilot) forecrop the advantage had the combined deep tillage system - by 4.2 mg / kg, the mouldboard minimum - by 6.4, the combined minimum - by 12.4 mg / kg (in the control - 107.6 mg / kg) in the tillering phase - by 6.6; 12.2; 8.0 mg / kg, respectively (control - 106.2 mg / kg).

Changes in the agrophysical parameters of the soil characterize the processes occurring in the soil under the influence of the system of its cultivation. When assessing the structural state of the soil, it was revealed that the average indicators for the content of agronomically valuable aggregates most resistant to the erosion effect of water (1-3 mm), depending on the conditions of the year, varied within insignificant limits: 2015 - 33.1%, 2016 - 34, 2, 2017 - 34.5, 2018 - 35.5, 2019 - 33.8% (see Table 5).

Табл. 4. Содержание K_2O в посевах яровой мягкой пшеницы Сибирский Альянс в слое почвы 0–40 см по фазам развития растений (2015–2019 гг.), мг/кг почвы

Table 4. K_2O content in spring soft wheat crops Siberian Alliance in soil layer 0–40 cm, mg/kg of soil, by plant development phases (2015–2019)

Soil tillage system	Before sowing	Tillering phase	Earing phase
Complete fallow forecrop			
Deep mouldboard (control)	108,8	95,2	106,2
Deep combined	113,2	101,2	117,0
Minimum combined	112,6	102,8	110,0
Minimum mouldboard	105,2	92,4	104,2
Green manure fallow (rapeseed grass)			
Deep mouldboard (control)	102,0	116,4	111,6
Deep combined	108,6	120,8	113,6
Minimum combined	105,6	104,0	110,4
Minimum mouldboard	89,0	105,0	111,0
Green manure fallow (melilot)			
Deep mouldboard (control)	107,6	106,2	116,0
Deep combined	111,8	112,8	116,0
Minimum combined	120,0	114,2	110,8
Minimum mouldboard	114,0	118,4	116,6

Average by factors, mg/kg of soil: K_2O, tillage system: deep mouldboard -107.8, deep combined - 112.8, minimum combined - 110, minimum mouldboard - 106.2; developmental phases: pre-sowing - 108.2, tillering phase - 107.4, earing phase - 111.9; forecrop: complete fallow - 105.7, green manure fallow (rapeseed) - 108.2, green manure fallow (melilot) - 113.7; LSD 05 by factors, mg/kg soil: tillage system - 4.39, forecrop -3.80, development phases - 3.80.

The influence of the soil cultivation system on the content of agronomically valuable aggregates is noted - 10.1%, the interaction of the soil cultivation system and the predecessor enhances this effect to 40.6%.

On average for 2015-2019, depending on the tillage system, the figures for the content of agronomically valuable aggregates are as follows: mouldboard deep tillage - 36.0%, combined deep tillage - 31.9%, combined minimum - 35.1, mouldboard minimum tillage - 34.0%; by forecrops: complete fallow - 32.9%, green manure fallow (rapeseed) - 34.5, green manure fallow (milelot) - 35.3%.

There is now a clear trend towards minimal tillage and direct seeding [24]. Tillage minimization did not worsen the state of soil aggregate composition: with combined minimum and mouldboard minimum systems, the number of agronomically valuable aggregates was at the control level (mouldboard deep). Soil texture can be characterized not only by the number of valuable aggregates, but also by the texture coefficient, which shows the ratio of agronomically valuable aggregates to the sum of the clumpy and dusty fractions. Higher coefficients of structure with mouldboard deep system (control) - 2,54, combined minimum - 2,47, mouldboard minimum - 2,23 on preceding green manure fallow (rapeseed) (see table 6).

An increase in the coefficient of soil structure for the complete fallow forecrop was found when using combined and mouldboard minimum tillage systems - 2.21 and 2.11 respectively, when using mouldboard deep tillage (control) - 1.66. The effect of the tillage system on the soil structure coefficient was 19.3% and that of the forecrop - 3.65. The greatest influence is determined by the interaction of these two factors - 34.4%. By applying organic matter, the use of green manure crops improves soil structure. For the preceding complete fallow (rapeseed) when using mouldboard deep soil tillage the coefficient of structure was 2.54 and for melilot it was 2.98.

With the increase of the coefficient of structure there was a decrease of the density of the soil, r = -0.3499 (R = 0.5760), which is important in assessing its agrophysical properties.

Табл. 5. Содержание агрономически ценных агрегатов (1–3 мм), % от воздушно-сухой почвы
Table 5. Content of agronomically valuable aggregates (1–3 mm), % of air-dry soil

Soil tillage system	2015	2016	2017	2018	2019
Complete fallow forecrop					
Deep mouldboard (control)	32,8	30,7	23,0	31,2	31,9
Deep combined	31,8	32,6	32,3	33,3	32,2
Minimum combined	33,9	35,8	34,4	36,0	36,2
Minimum mouldboard	29,8	34,4	37,2	34,1	34,4
Green manure fallow (rapeseed grass)					
Deep mouldboard (control)	32,4	32,0	39,6	37,7	38,1
Deep combined	29,7	33,8	31,1	31,9	31,6
Minimum combined	37,5	40,0	34,8	35,2	36,9
Minimum mouldboard	29,7	28,5	35,2	37,0	37,7
Green manure fallow (melilot)					
Deep mouldboard (control)	40,5	42,2	48,5	46,2	33,2
Deep combined	30,4	33,2	30,5	33,4	30,8
Minimum combined	32,7	31,6	33,6	34,6	32,9
Minimum mouldboard	36,2	36,1	34,4	35,2	29,9

Average by factors, %: agronomically valuable particles 1-3 mm: soil tillage system: deep mouldboard -36.0, deep combined - 31.9, minimum combined - 35.1, minimum mouldboard - 34.0; forecrop: complete fallow - 32.9, green manure fallow (rapeseed) - 34.5, green manure fallow (melilot) - 35.3; research year: 2015 - 33,1, 2016 - 34,2, 2017 - 34,5, 2018 - 35,5, 2019 - 33,8. LSD 05 by factors, mg/kg of soil: tillage system - 2.4, forecrop -2.1, years - 2.7.

Табл. 6. Коэффициент структурности почвы
Table 6. Soil pedality coefficient

Soil tillage system	2015	2016	2017	2018	2019	2015–2019
Complete fallow forecrop						
Deep mouldboard (control)	2,1	1,55	1,34	1,70	1,60	1,66
Deep combined	1,94	1,58	1,78	1,75	1,57	1,72
Minimum combined	2,1	2,24	2,15	2,15	2,39	2,21
Minimum mouldboard	1,58	2,1	2,68	2,05	2,16	2,11
Green manure fallow (rapeseed grass)						
Deep mouldboard (control)	1,97	2,39	2,78	2,32	3,22	2,54
Deep combined	1,58	1,62	1,44	1,47	1,56	1,53
Minimum combined	2,87	3,03	1,90	1,86	2,69	2,47
Minimum mouldboard	2,60	1,57	2,26	2,26	2,45	2,23
Green manure fallow (melilot)						
Deep mouldboard (control)	2,82	3,01	3,89	3,20	1,98	2,98
Deep combined	1,59	2,12	1,69	1,72	1,98	1,82
Minimum combined	1,75	1,82	1,75	1,78	2,00	1,82
Minimum mouldboard	2,28	2,08	2,19	2,25	1,60	2,10

Factor average, coefficient of structure, soil tillage system: deep mouldboard -2.39, deep combined - 1.69, minimum combined - 2.16, minimum mouldboard - 2.14; forecrop: complete fallow - 1.93, green manure fallow (rapeseed) - 2.19, green manure fallow (melilot) - 2.17; year of research: 2015 - 2,10, 2016 - 2,09 , 2017 - 2,15, 2018 - 2,04, 2019 - 2,10. LSD 05 by factors: tillage system - 0.30, forecrop -0.34, year - 0.26.

Табл. 7. Плотность сложения почвы (2015–2019 гг.), г/см³
Table 7. Soil bulk density (2015–2019)

Soil tillage system	Soil density in the soil layer 0-40 cm
Complete fallow forecrop	
Deep mouldboard (control)	1,00
Deep combined	1,01
Minimum combined	1,00
Minimum mouldboard	1,04
Green manure fallow (rapeseed grass)	
Deep mouldboard (control)	1,02
Deep combined	1,05
Minimum combined	0,98
Minimum mouldboard	0,98
Green manure fallow (melilot)	
Deep mouldboard (control)	1,00
Deep combined	1,07
Minimum combined	0,98
Minimum mouldboard	1,02

Average by factors, soil density: tillage system: deep mouldboard - 1.01, deep combined - 1.04, minimum combined - 0.99, minimum mouldboard - 1.01; forecrop: complete fallow, green manure fallow (rapeseed) -1.01, green manure fallow (melilot) - 1.02. LSD 05 by factors: tillage system - 0.05, forecrop - 0.04.

The optimum equilibrium bulk density for the main subtypes of chernozems is 1.00-1.25 g/cm³. At these values, it is possible to use minimum tillage technologies [25].

The bulk density of the soil was between 1.00 and 1.04 g/cm³ for the complete fallow crop. An increase of 0.04 g/cm³ was noted with the mouldboard minimum tillage system (see Table 7).

There is a tendency to reduce the bulk density of soil to 0,98 g/cm³ on the forecrop green manure fallow (rapeseed) at minimum tillage: combined and minimum mouldboarding, and at mouldboard deep (control) - 1,02 g/cm³. An increase in soil bulk density by 0.01-0.07 g/cm³ was recorded for all studied forecrops when using a combined deep tillage system. The conditions of the year had a significant impact on soil bulk density - 55.9 %, the tillage system - 11.1 %. As a result of the correlation analysis it was found that a decrease in P_2O_5 content, r = -0.4898; K_2O, r = -0.2530, occurs with increasing soil bulk density.

CONCLUSIONS

1. The highest content of nitrate nitrogen before sowing of spring soft wheat in the forecrop of green manure fallow (rapeseed), green manure fallow (melilot), complete fallow when using the mouldboard minimum tillage system exceeded the control (mouldboard deep tillage) by 2.1; 5.4 and 6.8 mg/kg of soil, respectively.

2. The advantage in the content of N-NO3 during the tillering period of spring soft wheat was noted in the forecrop of green manure fallow (melilot) and green manure fallow (rapeseed) with the use of the mouldboard minimum tillage system (in the autumn it was embedded in green manure fallow BDT-3) - 27,9 and 28,3 mg/kg of soil, respectively. The influence of the tillage system on the nitrate nitrogen content in the soil during the bushing stage of the spring soft wheat was 15,5%, the influence of the conditions of the year was 12,9, and the interaction of these factors was 20,1%.

3. When spring soft wheat plants used nitrate nitrogen from heading stage to earing stage, its content decreased on average by 35.7% in the

experiment (from 21.6 to 13.9 mg/kg of soil). The effect of the tillage system on the nitrate nitrogen content in the soil during the earing phase was 10.7%; the effect of the forecrop was not detected. The highest nitrate nitrogen content was recorded under mouldboard minimum tillage for forecrop rapeseed - 16.8 mg/kg, the control - 14.5 mg/kg.

4. High P_2O_5 content (from 150 mg/kg and higher) was found on average for 5 years during earing phase, from 145.0 to 165.6 mg/kg; maximum values were obtained for green manure fallow (rapeseed) with combined minimum tillage - 160.6 mg/kg and mouldboard minimum - 165.6 mg/kg, with mouldboard deep (control) - 150.6 mg/kg of soil. The share of the influence of the tillage system on the content of mobile phosphorus was 5.1% and that of the forecrop 2.8%. A positive relationship between the content of nitrate nitrogen in the soil and the amount of mobile phosphorus on the forecrop green manure fallow (rapeseed), r = 0.7118-0.8917 (R = 0.9500) was revealed.

5. A significant increase in the content of exchangeable potassium compared to the control average for 2015-2019 was observed with the combined deep tillage system - 5.0 mg/kg (LSD_{05}), with the other studied systems the indicators were at the control level. The effect of the tillage system on the exchangeable potassium content was 7.5%, that of the forecrop 18.5, and the interaction of these factors was 12.3%.

6. The effect of the tillage system on the content of agronomically valuable aggregates most resistant to the erosive action of water (1-3 mm) - 10.1% was noted. The interaction of tillage system and forecrop increases this effect by up to 40.6%. On average for 2015-2019, depending on the tillage system, the rates of agronomically valuable aggregates content were as follows: mouldboard deep tillage - 36.0%, combined deep tillage - 31.9%, combined minimum - 35.1%, mouldboard minimum tillage - 34.0%; by forecrop: complete fallow - 32.9%, green manure fallow (rapeseed) - 34.5%, green manure fallow (melilot) - 35.3%.

7. Higher coefficients of structure at mouldboard deep tillage (control) - 2.54, combined minimum - 2.47, mouldboard minimum - 2.23 on the forecrop green manure fallow (rapeseed), green manure fallow (melilot) - 2.98 (mouldboard deep tillage) were noted.

8. The effect of the tillage system on the soil structure coefficient was 19.3% and that of the forecrop 3.65%. The greatest influence is determined by the interaction of these two factors - 34.4%. With the increase of the coefficient of structure there was a decrease of the bulk density of the soil, r = -0.3499 (R = 0.5760), which is important in assessing its agrophysical properties.

9. A tendency has been revealed to reduce the bulk density of soil to 0.98 g/cm^3 for the forecrop green manure fallow (rapeseed) with minimum tillage: combined and minimum mouldboarding tillage, deep tillage (control) - 1.02 g/cm^3. An increase in soil bulk density by 0.01-0.07 g/cm^3 was recorded for all studied crops when using a combined deep tillage system. Annual conditions had significant influence on the soil bulk density - 55,9 %, and the tillage system - 11,1 %. As a result of correlation analysis, it was found that P_2O_5 content, r = -0.4898, K_2O, r = -0.2530 decreases with increasing bulk density of the soil.

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