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Fertility of Arable Chernozems of Western Siberia During Long-Term Application of Mineral Fertilizers

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Abstract **—Western Siberia is the area of risk farming; however, it has always been and still remains a promising region for the development of modern agriculture. Unlike well-developed European chernozem or black soil, their Siberian counterparts are unstable to the anthropogenic impact. Therefore, the farming technologies for growing crops developed for the Central Black Earth Region are not acceptable for Western Siberia.**

Studies on the influence of increasing doses of mineral fertilizers were carried out in the Department of Soil Science and Agrochemistry of the Northern Trans-Ural State Agricultural University located in the forest-steppe zone of the Trans-Urals. These studies covered the application of fertilizers for the planned yield from 3.0 to 6.0 t/ha of crops in the period from 1995 to 2015. Partial migration of nitrate nitrogen outside the arable layer was identified. The transition of phosphorus fertilizers non-demanded by plants to phosphate forms that are inaccessible to them was revealed, which indicates the need for justification of doses of mineral fertilizers in the fields of Western Siberia.

The negative effect of high doses (more than N120P30 kg/ha) on the agrochemical and agrophysical properties of arable balck soil in the Northern Trans-Ural region was revealed. For the period of 20 years the content of agronomically valuable aggregates (1.00-0.25 mm) has decreased from 89.9 to 76.5 mm, and their water resistance has droped down from 75.4 to 66.0%. Under the influence of mineral fertilizers, the rate of compaction of the arable horizon increases by 7.0% with respect to the natural soil fertility.

Keywords — agrophysical properties, structural and aggregate composition, nutrient mode, crops, planned yield

I. Introduction

Black soils or chernozems combine optimal properties and favorable modes which makes it possible to grow all agricultural crops with minimal costs [1, 2]. The area of chernozems in Western Siberia is not that great; howevwer, their role in the agriculture of the region and country as a whole is enormous. Siberian chernozems began to be studied as far back as the 19th century and by now the regional features of their occurrence, as well as modern properties that determine their high fertility are already known. However, there is a significant gap in the field of agricultural use of Siberian chernozems since they have been recently developed in comparison with the European analogues [3]. There are a lot of reasons for this among which several main ones are identified. These are constantly changing technologies for cultivating crops from crop rotations, tillage systems and to different intensity of agrochemical application [4, 5]. In Siberia, there is no comprehensive (deployed in space) system for long-term stationary observations, which could help identify regional features of the anthropogenic evolution of chernozems. The available information on the impact of some elements of agriculture is often presented by studies carried out in the period of 3-5 years [6]. The existing soil facilities with the age of more than 10 years make it possible to determine the reliable influence of agriculture on the fertility of Siberian chernozems, especially in the field of humus formation.

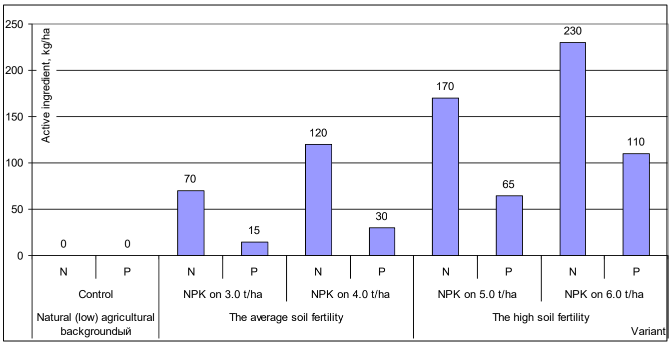

Fig. 1. Average doses of mineral fertilizers for obtaining planned yield of spring wheat, kg of active material per 1 ha (1995-2015)

As for the influence of mineral fertilizers on the fertility of soils concerns there is no univocal opinion. There is a point of view about their positive effect. The supporters of this idea cite data on the positive balance of humus and improved physical and chemical properties [7]. Some researchers are convinced that systematic use of mineral fertilizers leads to deterioration of the effective fertility which include nutrient regimes as well as agrophysical and water-physical properties. There is also another group of scientists who maintain the idea that mineral fertilizers in doses that are commonly used by enterprises of Siberian agribusiness industry cannot have any significant impact on the fertility of chernozems. In our opinion all these points of view are worth looking at and have a right to exist.

The scientific experience of the influence of mineral fertilizers on the fertility of chernozem soils carried out in the Northern Trans-Ural State Agricultural University can be considered as a significant one. It relies on stationary observations covering a time span of 20 to 50 years. Therefore, at present time it is possible to draw appropriate conclusions about the influence of different elements of agriculture on the fertility of the Siberian chernozems. In one of the fasilities of the Department of Soil Science and Agrochemistry, which was established in 1995, the effect of increasing doses of mineral fertilizers on the productivity and fertility of leached chernozem is studied.

The aim of the research is to study the influence on the increasing doses of mineral fertilizers applied to grain crops on the elements of fertility of leached chernozem.

II. Subjects and Methods

The research was carried out in the experimental field of the Northern Trans-Ural State Agricultural University which is located in the northern forest-steppe of the Trans-Ural region (12 km from Tyumen). The soil of the experimental site is heavy loamy leached chernozem. The average thickness of humus horizon is 30-35 cm; the humus content in 0-20 cm layer is 6.00%; in 20-40 cm layer it is 3.77%. The content of nitrate nitrogen before the experiment in 0-40 cm layer did not exceed 5.0 mg/kg of soil over the years of investigation. The mobile phosphorus and potassium content in 0-40 cm layer was 70 and 150 mg/kg of soil which corresponded to the average and increased availability of crops with these nutrients. Agrophysical rates and morphogenetic properties of soil are characteristics for chernozems in Western Siberia [5]. The studies began in 1995 and continue to the present. The experiment provides for the introduction of mineral fertilizers based on the calculations of planned yield of crops, i.e. 3.0, 4.0, 5.0 and 6.0 t/ha. Natural soil fertility is used to monotor and control the process (option without mineral fertilizers). The doses are calculated annually following the results of the agrochemical analysis of soil carried out in the spring period by the elementary balance method. The average doses of fertilizers are shown in Fig. 1. In the experiment, both ammophos and ammonium nitrate were used which were introduced in spring under pre-sowing cultivation. After harvesting the crops, the straw was plowed (option based).

The tillage system is a dump tillage of non-uniform depth (25-27 cm is for seeded fallow, 20-22 cm is for crops). Crop rotation is cereal with seeded fallow and alternating crops: annual grasses (pea-oats); spring wheat and oats. During the years of research, the crop rotation has not changed. The sowing area of each plot is 100 m^2; accounting area is 50 m^2. The plots are fixed and the placement is consecutive. The experience was carried out in 4 repetitions.

The nitrate nitrogen was determined in the soil on the basis of disulfophenol method; the mobile phosphorus was determined using the extract of acetic acid (0.5N) and ammonium molybdate; potassium was determined with the same extract using fiery photometer. The analysis on bulk density and the structural-aggregate composition of the arable horizon was carried out according to Kachinsky (six times at each repetition). Computation of obtained results was carried out by the dispersion method using the Microsoft Excel software product.

III. Results

The supply of nitrate nitrogen on average during the years of research was very low, i.e. 5 mg/kg of soil before sowing crops (Table 1). The reserves of nitrates in 0-40 cm layer corresponded to 25-30 kg/ha, which is a characteristic of chernozem soils of Siberia [8, 9]. In case of soil fertility, the content of nitrate nitrogen has increased up to 12 mg/kg of soil in tillering, which corresponded to average availability. Calculations showed that due to microbiological activity during the sowing-tillering period, 34 kg/ha of nitrogen available for plants was formed which is half the value of current nitrification of chernozems of the Trans-Urals [10]. When fertilizers were applied, the nitrate content in 0-40 cm layer during the tillering period reached 26-51 mg/kg of soil. It should be noted that the maximum was reached with 4.0 t/ha NPK. When fertilizers were introduced for the planned yield of 6.0 t/ha, a lower content of 29 mg/kg of soil was observed. This is explained by the migration processes of nitrates into the depth and incomplete dissolution of ammophos during this period. By the time of flowering, the nitrogen concentration decreases which is due to its consumption by wheat agrophytocenosis. During the monitoring period this value reaches initial value; whereas, on the fertilized soils this value amounts to 9-36 mg/kg of soil, the maximum value was in the plots where fertilizers were applied for the planned yield of 6.0 t/ha.

During grain filling and ripening, spring wheat actively consumes nutrients and reacts adversely to nitrogen deficiency. Before harvest time, the concentration of nutrient is reduced to the lowest possible values amounting to 2 mg/kg of soil. Taking into account the fact that half of the nitrogen of current nitrification is accounted for this period it can be claimed that crops growing on chernozems in the northern forest-steppe of the Tyumen region without mineral fertilizers would be a limiting factor regarding the increase of the cropping power of arable land. Very low availability of nitrate nitrogen in the second half of vegetation can be a convincing argument for the use of nitrogen fertilizing in any form convenient for farming.

In case of fertilization for a planned yield of up to 4.0 t/ha of crops, the nitrogen content in 0-40 cm layer after harvesting remains slightly above the initial values of 7-8 mg/kg of soil, which proves the effectiveness of nitrogen absorption by wheat agrophytocenosis. In case of fertilization for a planned yield of up to 5.0 and 6.0 t/ha, the nitrogen content after harvesting remains quite large and amonts to 8-10 mg/kg of soil, which in the conditions of the Northern Trans-Ural region can lead to the loss due to migration under the effect of downward movement of water in the autumn-winter period .

TABLE I. DYNAMICS OF NUTRIENT CONCENTRATION APPLYING INCREASED DOSES OF MINERAL FERTILIZERS FOR A PLANNED YIELD OF SPRING WHEAT, MG/KG OF SOIL (1995-2015)

Variant	Before sowing			Tillering			After harvesting		
	N	***P***	***K***	***N***	***P***	***K***	***N***	***P***	***K***
Without fertilizers	5	70	148	12	74	174	2	37	125
3.0 t/ha NPK	5	76	148	26	82	184	5	82	136
4.0 t/ha NPK	5	80	164	51	107	192	7	90	177
5.0 t/ha NPK	5	76	148	48	148	195	8	109	150
6.0 t/ha NPK	5	83	157	29	121	190	10	138	140

For a twenty-year period of systematic use of mineral fertilizers a significant increase in the phosphorus content in 0-40 cm layer was recorded only when mineral fertilizers were used for the planned yield of 6.0 t/ha. On average, over the years of research this value before planting spring wheat has reached 83 mg/kg of soil, which was 20% higher than control values. The reason for the lack of accumulation effect could be the method of calculation of fertilizer doses based on the annual monitoring of nutrient-supplying capacity.

The concentration of mobile phosphorus before sowing the spring wheat was 70 mg/kg of soil, which corresponded to the average supply of this nutrition. By the time of tillering the content of phosphates available for plants did not increase (deviations were within the measurement error). Later on this indicator has gradually decreased and reached a minimum rate after wheat harvesting, amouting to 37 mg/kg. It should be noted that during the autumn-spring period partial restoration of reserves takes place in the fields due to the transition of phosphorus, as well as calcium and iron triphosphates from organomineral compounds [11, 12]. This explains the annual increase in mobile phosphates before sowing crops.

When mineral fertilizers were applied, the concentration of mobile phosphates during tillering has increased up to 82-148 mg/kg of soil, which resulted in phosphoric feeding of crops. According to the leaf nutrition diagnostics, when using calculated doses of mineral fertilizers, there is no phosphorus deficit in spring wheat. During flowering, the concentration of mobile phosphorus in fertilized samples continues to increase despite its constant absorption by plants. This fact is explained by the process of further dissolution of phosphorus fertilizers. By the time of harvesting, the concentration of phosphates available for plants in the soil is gradually decreasing. In the period of flowering and ripening the consumption of phosphorus by grains is insignificant; therefore, it is believed that the decrease occurs due to the transformation of monophosphates into di- and triphosphates of calcium or iron. This explains the decrease in the content of mobile phosphorus in fertilized samples before sowing conpared to the autumn of the previous year. This is a convincing evidence of ineffectiveness of phosphorus fertilizer application in high doses in the area of chernozems since the unused portion of phosphorus will be transformed into hard-to-reach compounds.

Since the potassium fertilizers were introduced only during the first years of research with a planned yield of 5.0 and 6.0 t/ha, the potassium regime in the experiment was formed from the biogenic carry-over and straw plowdown. Basing on the previous calculations, a large part of potassium, which was absorbed by crops returns to the soil during the straw plowdown. In this experiment all the straw remained in the plots and was plowed. Before sowing, the potassium concentration ranged from 148 to 164 mg/kg of soil, which corresponded to an increased supply of nutrition element. During the development of spring wheat the content of mobile potassium has gradually decreased, reaching the minimum values before harvesting (125 mg/kg off soil). In case of fertilizer applications, this indicator either remained at the same level or partially increased due to gradual release from the straw.

Soil fertility is determined not only by the nutrient regime for plants, but also by water, air and thermal regimes, which depend to a large extent on the structural and aggregate state. The study of these indicators is necessary for developing plant nutrition. The development of computer technology allows this to be done in the shortest possible time [13, 14].

The analysis of structural state was carried out after each rotation of the crop rotation. However, to demonstrate and identify the influence of mineral fertilizers, data for the time period of 20 year have been provided. In the year of harvesting (1995), both structural and aggregate state of the arable horizon of leached chernozem was good and corresponded to the chernozems of the Trans-Urals. The concentration of agronomically valuable aggregates at dry sifting varied in the range of 85.7-91.3%; water resistance was 75.4-82.4% of the total mass (Table 2). In the absence of fertilizers and the straw plowdown, the structural and aggregate composition of the arable layer has not undergone changes for almost 20 years, which means that deviations were minimal.

As shown by dry sieving, the systematic use of mineral fertilizers for a planned yield of 3.0 t/ha did not lead to soil structure deterioration; however, the water resistance of soil aggregates decreased from 82.4 to 76.9% due to qualitative composition change of humic substances [15, 16].

Further increase in the level of mineral nutrition adversely affected both quantitative and qualitative characteristics of the structural aggregate composition of arable chernozem. The most interesting was the sample with maximum saturation of fertilizers. For the period of 20 years the content of aggregates during dry sieving has decreased from 89.9 to 76.5%; water resistance has decreased from 75.4 to 66.2%. This fact is explained by the dispersive influence of high doses of ammonium nitrate on the soil structure. This is a convincing argument for rejecting high doses of mineral fertilizers under the existing fertilizer system.

TABLE II. STRUCTURAL AND AGGREGATE COMPOSITION OF ARABLE LAYER OF CHERNOZEM LEACHED DURING LONG-TERM USE OF INCREASING DOSES OF MINERAL FERTILIZERS

Type	Sieving method	Year	Size if aggregates (mm) and their concentration (% mass)		
			>10	*10-0.25*	*<0.25*
Free from fertilizer	Dry	1995	5.3	85.7	9.0
		2015	6.5	82.3	11.2
	Wet	1995	4.1	75.6	20.3
		2015	5.3	76.2	18.5
3.0 t/ha NPK	Dry	1995	4.4	88.2	7.4
		2015	3.8	87.3	8.9
	Wet	1995	3.9	82.4	13.7
		2015	7.8	76.9	15.3
4.0 t/ha NPK	Dry	1995	3.1	91.3	5.6
		2015	5.8	71.6	22.6
	Wet	1995	3.2	78.6	18.2
		2015	11.5	70.8	17.7
5.0 t/ha NPK	Dry	1995	7.6	88.3	4.1
		2015	9.8	77.1	13.1
	Wet	1995	3.4	80.7	15.9
		2015	2.7	73.1	24.2
6.0 t/ha NPK	Dry	1995	4.8	89.9	5.3
		2015	7.5	76.5	16.0
	Wet	1995	5.3	75.4	19.3
		2015	8.2	66.2	25.6

In Western Siberia many scientists have worked on determining the optimal soil bulk density. According to V.F. Trushin and E.F. Krylov, the optimal density of chernozem for most cultivated crops is 1.20-1.26 g/cm^3. Since this indicator is directly dependent on the structural and aggregate composition, the effect of high doses of mineral fertilizers would be quite obvious. To better understand changes in the soil density, it is better to use the strength compaction factor, which indicates the degree of compaction in a certain period. In this case, this indicator was considered during the sowing period.

TABLE III. BULK DENSITY OF ARABLE LAYER OF CHERNOZEM, G/CM3, (1995-2015)

Date of sampling	Monito ring	3.0 t/ha NPK	4.0 t/ha NPK	5.0 t/ha NPK	6.0 t/ha NPK
Before sowing	0.97	0.95	1.02	0.94	1.00
Tillering	1.08	1.05	1.09	1.04	1.13
Before harvesting	1.17	1.15	1.08	1.22	1.27
Srength compaction factor	1.11	1.11	1.07	1.11	1.13

Before the spring wheat sowing, the arable layer density varied from 0.94 to 1.02 g/cm^3 which corresponded to a friable state. This is due to a number of agrotechnical operations immediately before sampling. By the time of tillering, the arable layer has gradually thickened up to 1.04-1.13 g/cm^3. The minimum rate of soil shrinkage was observed at a planned yield of 4.0 t/ha where the strength compaction factor factor was 1.07 while the monitored value compised 1.11 units. The effect of fertilizers was noticeable only when the mineral nutrition (6.0 t/ha NPK) was at its maximum level, i.e. the compaction rate corresponded to the rete of 1.13 units.

By the time of harvesting, the influence of high doses of fertilizers on the bulk density became apparent. In case of 5.0 and 6.0 t/ha NPK, the arable layer was compacted to 1.22 and 1.27 g/cm^3, while during monitoring it was 1.11 g/cm^3. The strength compaction factor during this period was 1.27-1.30 units which is 7% more compared to the monitored values. Despite the compacting effect of mineral fertilizers, the aggregate density was within the optimum range for crops.

IV. CONCLUSION

As a result of long-term stationary studies it was established that under the existing system of farming (crops with seeded fallow crop rotation, dumping soil processing system, straw plowdown), the absence of mineral fertilizers leads to a gradual deterioration of the nitrogen and phosphorus regime of arable chernozem. The supply of nitrate nitrogen throughout the entire vegetation of spring wheat is very insignificant. The introduction of mineral fertilizers based on the planned yield of 3.0 and 4.0 t/ha favorably affects the nutrient regime and the agrophysical properties of arable chernozem of forest-steppe zone of the Trans-Urals. A further increase in the level of mineral nutrition leads to a partial loss of nitrate nitrogen as a result of its leaching outside the root zone. In the case of the lack of demand, phosphorus introduced with fertilizers is transfered into forms inaccessible to plants. The straw plowdown on fertilized soils positively affects the potassium regime of leached chernozem. High doses of mineral fertilizers have a dispersive effect on the structural aggregates of arable layer, which may entail worsening of agrophysical properties of chernozem soils of northern Trans-Urals. For the period of 20 years the content of agronomically valuable aggregates with annual application of mineral fertilizers in doses exceeding N120P70 has decreased from 90 to 77%; water resistance of aggregates has decreased from 75.4 to 66.2%. The deterioration of structural-aggregate composition of arable layer of leached chernozem facilitated the acceleration of compaction processes after mechanical tillage. In Western Siberia this can lead to the disturbance of water regime and decrease in fertility of arable chernozems.

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