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Phosphoric regime of light chestnut soil and sugar beet yield with long-term use of phosphorous fertilizers

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Abstract

This study presents the results of research on the effect of long-term use of phosphorus fertilizers on permanent sugar beet crops for more than 50 years and on the transformation of phosphate forms on light chestnut soil and its yield. Our work aims to establish the main factors of quantitative and qualitative changes in various phosphates in light chestnut soil. Despite the large amount of practical material, the influence duration of phosphorus fertilizer application has not been sufficiently studied on the irrigated soils of Kazakhstan. It should be noted that the current study was carried out in long-term stationary experimental sites for the production of sugar beet with permanent sowing. The introduction of phosphate fertilizers primarily on the permanent crops of sugar beets in the same norms contributes to a more significant increase in gross phosphorus reserves. The soil content of gross phosphorus for 58 years on the control and nitrogen-potassium variants show practically no changes. Furthermore, when phosphorus fertilizers are applied on the variant with the annual application of a single norm of phosphorus and its amount for 58 years (4400 kg·ha^{-1} of application doses) its content increased by 2660 mg·kg^{-1}, and with the introduction of its one and a half norms (6600 kg of application doses) by 2860 mg·kg^{-1} of soil.

Key words: *ammonia nitrogen, chestnut soil, fertilization, gross phosphorus, mineral nitrogen, mineral phosphorus, mobile phosphorus, organic phosphorus, permanent sugar beet crop*

INTRODUCTION

There is a problem of phosphorus in agriculture, the solution to which is associated with the knowledge of its various forms in the soil and their transformation, the ways of its mobilization, and the conditions for the most effective use of phosphorus fertilizers in our and other countries, has been the topic of several studies [MAHFOUD *et al*. 2020; SMIT *et al*. 2009; TIRADO, ALLSOPP 2012]. Within the literature, there is a lot of data on the forms of various phosphates and their quantitative content in different soils. A wide variety of combinations and factors of soil formation, the contrast of soil and climatic conditions determine the diversity of forms of phosphorus compounds in soils. Numerous materials have been published on the content, reserves, and forms of soil phosphates in the soils of our country that were obtained as a result of both short-term and long-term studies [FARMER 2018; MENEZES-BLACKBURN *et al*. 2018; NOSKO 2017].

The purpose of our work is to establish the main factors of quantitative and qualitative changes in various phosphates in light chestnut soil depending on the long-term (more than 58 years) application of phosphorus fertilizers on the permanent sowing of sugar beet.

An important indicator of potential soil fertility is the content of gross phosphorus in various soils. Gross reserves of phosphorus in soils are very large compared with that needed for the crops. However, all types of soils need phosphorus fertilizers because this indicator cannot be used to judge the degree of mobility and phosphorus availability in soils [BURZYŃSKA 2019; XIN *et al*. 2019]. On the field of permanent crops of sugar beet, the experimental scheme was as follows: 1 control; 2NK; 3NPK; 4NP1.5K. The annual fertilizer rate was (in kg·ha^{-1}) N – 100, P – 80, K – 70.

In the nutrition of cultivated plants, the most important place is given to the organic and mineral forms of phosphorus, which are constantly in the process of interchanging with one another. The organic part of phosphorus represents the main component of the "working capital" of soil phosphates and, under certain conditions, can be mineralized, enriching the soil with mineral forms of phosphorus [CHEN *et al*. 2014; JONER 2000; PLATTS, LEONG 2020; STAMENKOVSKA *et al*. 2019].

MATERIALS AND METHODS

The research was carried out in long-term stationary experimental sites for the productivity of sugar beet with its permanent sowing, which has been in place since 1961 in 8-field beet rotation and permanent sowing in irrigated light chestnut soil.

The agrochemical characteristic of light chestnut soil in the experimental plot during the laying of the experiment was as follows: the humus content in the arable layer of the soil – 2.348%, of the total nitrogen 0.227%, phosphorus 0.221%, potassium 1.9%, easily hydrolysed nitrogen – 90–100 mg, mobile phosphorus (according to Machigin) 24 mg·kg^{-1}, exchange potassium 558 mg·kg^{-1} of soil, CO_2 of carbonates 3.0–4.3% [SHIBIKEYEVA *et al*. 2015]. Irrigated chestnut soils of Zailiyskiy Alatau in natural conditions are characterized by moderate activity of hydrolytic and redox enzymes [ELESHEV, BAKENOVA 2012].

On the field of permanent crops of sugar beet, the experimental scheme was as follows: 1 control; 2NK; 3NPK; 4NP1.5K. The annual fertilizer rate was N – 100, P – 80, K – 70 kg·ha^{-1}.

Phosphorus fertilizers were introduced in the forms of simple and double superphosphate, nitrogen-ammonia nitrate and urea, potassium chloride, and potassium salt.

The size of the plot was 216 m^2. The repeatability of the experiment was 4-fold. Agricultural technology in the experiments was generally accepted for the zone. The variety of sugar beet was 'Ardan'. Analytical studies were performed in an accredited laboratory (No. Kz.I. 04. 1403).

In soil samples, we determined the total phosphorus by K.E. Ginzburg and K.A. Shcheglova with further colometrization by Denizza, mobile phosphorus – by the method of B. P. Machigin; gross phosphorus – by the method of META; organic phosphorus by Lito–Chango–Jackson and Hedley; composition of mineral phosphorus by Ginzburg and Lebedeva [GINZBURG 1981; GINZBURG, LEBEDEVA 1971; MACHIGIN 1940].

The size of the harvest was worked out by dividing the subsequent reduction to 100% purity. It should be noted that conventional methods processed the crop data. The sugar content was determined by the polymetric method.

RESULTS AND DISCUSSION

Despite the large amount of material, the influence of the phosphorus fertilizers application and duration has not sufficiently studied on the irrigated soils of Kazakhstan. The available single data on the impact of the duration of fertilizers application relates to the aspect of assessing their effect on the yield and quality of crops and partly on the phosphate regime of soils. Most studies were conducted in short-term field experiments, which are designed primarily to establish specific doses of fertilizers on crop productivity.

These field studies were performed on rather narrow backgrounds and periods of variation of soil fertility characteristics, which did not establish the qualitative and quantitative composition of phosphates and their functional relationship between the level of potential and effective fertility [GUREEV 2011; MUKHINA *et al*. 2010].

BASIBEKOV and TORCHINA [1978] and YELESHEV and IVANOV [1987] conducted the first studies on this topic in 1961–1975. The data showed a significant change in the qualitative and quantitative composition of phosphorus compounds because of the use of phosphorus fertilizers for 15 years (Tab. 1).

The increase in gross reserves of phosphorus during its long-term use was mainly depended on the fertilizer norm. The more phosphorus introduced through fertilizers, the more it accumulates in the soil (see Tab. 1). In the initial background, the content of gross phosphorus was 0.203% (2210 mg·kg^{-1}), when phosphorus fertilizers were applied in the norm of 780 kg over 15 years, the content of gross phosphorus in the 0–20 cm layer was 0.229% (2400 mg·kg^{-1}). The introduction of 1170 kg of phosphorus led to 0.285% (2480 mg·kg^{-1}). In the variant without phosphorus fertilizers, the content of gross phosphorus decreased from 0.221 (2270 mg·kg^{-1}) to 0.218% (2260 mg·kg^{-1}).

The introduction of phosphate fertilizers primarily on the permanent crops of sugar beets in the same norms contributes to a more significant increase in gross phosphorus reserves. The soil content of gross phosphorus for 58 years on the control and nitrogen-potassium variants practically does not undergo changes. When phosphorus fertilizers are applied on the variant with the annual application of a single norm of phosphorus and this amount for 58 years (4400 kg·ha^{-1} of application doses), its content increased by 2660 mg·kg^{-1}, and with the introduction of its one and a half norms (6600 kg of application doses) by 2860 mg·kg^{-1} of soil.

Organic phosphates in light chestnut soil in the initial background were 510 mg·kg^{-1}, whereas the applying phosphorus fertilizers in the norm of 780 kg and 1170 kg for 15 years was 460 mg·kg^{-1} under permanent crops of sugar beet. The application of phosphorus fertilizers does not contribute to the accumulation of organic phosphorus in the soil. On the contrary, it was reduced by 2.6–3.3% in comparison with the initial background. However, after 58 years, there was a significant increase in organic phosphates when applying phosphorus fertilizers in a single dose (597 mg·kg^{-1}) and a half dose (602 mg·kg^{-1}). The marked difference in the

Table 1. Transformation of phosphates in light chestnut soil with long-term use of phosphorus fertilizers on permanent sugar beet crops

Treatment				Original background, 1961	Permanent sowing of sugar beet							
					1961–1975 (15 years)				2017–2019 (58 years)			
					control	NK	NPK	NP1.5K	control	NK	NPK	NP1.5K
Applied in total P_2O_5 kg·ha^{-1} a.s.				0	0	0	780	1170	0	0	4400	6600
P_2O_5 in soil (0–20 cm)	gross (mg·kg^{-1})			2210	2270	2260	2400	2440	2100	2140	2660	2860
	organic (mg·kg^{-1})			510	460	460	460	460	480	500	597	602
	mineral (mg·kg^{-1})			1700	1810	1800	1940	1980	1815	1810	2063	2098
	mobile (mg·kg^{-1})			24.0	32.7	30.0	60.3	68.3	17.3	16.6	66.1	70.6
	mineral phosphates by Ginzburg and Lebedeva	CaP_I	P_2O_5 mg·kg^{-1} of soil	100	82	86	133	152	17.5	14.5	102.5	138.0
			% of the amount of mineral phosphates	7.9	6.3	6.3	8.8	9.5	1.4	1.1	6.5	8.2
		$Ca\text{-}P_{II}$	P_2O_5 mg·kg^{-1} of soil	282	294	318	375	397	256.5	263.0	435.0	455.0
			% of the amount of mineral phosphates	22.3	22.4	23.4	24.9	24.8	20.8	20.5	27.5	30.0
		$Ca\text{-}P_{III}$	P_2O_5 mg·kg^{-1} of soil	742	788	810	828	882	816	846.5	879.0	907.5
			% of the amount of mineral phosphates	58.7	60.2	59.5	55.0	55.1	66.2	60.0	55.6	53.8
		(Al+Fe)P	P_2O_5 mg·kg^{-1} of soil	141	146	147	169	170	142.5	160.0	164.5	187.0
			% of the amount of mineral phosphates	11.1	11.1	10.8	11.2	10.6	11.6	12.5	10.4	11.0
		sum of fractions		1265.0	1310.0	1361.0	1505.0	1601.0	1232.5	1284.0	1581.5	1687.5

Explanation: a.s. = active substance.
Source: own study.

change in organic phosphorus content could be due to the more intensive mineralization of organic matter in the "monoculture" soil.

Studies have shown that long-term use of phosphorus fertilizers has a significant impact on mobile phosphorus content in the soil.

When applying phosphorus fertilizers on permanent sugar beet crops, there was a greater accumulation of mobile phosphorus in the soil. Thus, when applying 780 and 1170 kg of P_2O_5, the content of mobile phosphorus increased in the 0–20 cm layer by 2.0–2.1 (60.3–68.3 mg·kg^{-1}) times, in comparison with the control and by 2.5 times (24 mg·kg^{-1}) in comparison with the initial background.

The introduction of nitrogen-potassium fertilizers on the permanent crops of sugar beets does not affect the change in mobile phosphorus content in the soil. It is interesting to note that in the control variant in all experiments, mobile phosphorus content did not decrease to less than 14–15 mg·kg^{-1} of soil. However, soil depletion by mobile forms of phosphates was reflected in the development and appearance of plants. Subsequently, this led to a decrease in sugar beet yield.

The resulting decrease in sugar beet yields, can result in the assumption that the Machigin method with a mobile phosphorus content of less than 10–14 mg·kg^{-1} of soil does not reflect the true stock of phosphates assimilated by plants in the soil. In such cases, in order to determine the degree of soil availability with assimilable phosphorus, it is necessary to use the indicators of the fractional composition of mineral phosphates.

A study of the fractional composition of phosphates by Ginzburg and Lebedeva showed that the systematic application of fertilizers for 15 years led to the appearance of the content of "active" mineral phosphates in all age-related quantities of loose-bound ($Ca\text{-}P_I$) and different-base ($Ca\text{-}P_{II}$) calcium phosphates not in absolute, and in relative terms to gross phosphorus.

In the arable layer of soil without phosphorus fertilizers, the sum of loose-bound ($Ca\text{-}P_I$) and different-base phosphates ($Ca\text{-}P_{II}$) amounted to 30.2% of the sum of "active" mineral phosphates. After 15 years introduction of 780 and 1170 kg·ha^{-1} the phosphorus value increased to 34.2, 35.0%, respectively. The amount of phosphates of one and a half oxides remained practically unchanged, and the phosphates of high-base fractions decreased in relative terms to 55.2 and 54.3% from the use of 780 and 1170 kg·ha^{-1} of phosphorus fertilizers.

Research conducted in 2017–2019 shows a further enrichment of light chestnut soil with soil phosphates. Therefore, the data in Table 1 shows that there was also a significant change in the qualitative and quantitative composition of phosphorus compounds in the soil due to the use of phosphorus fertilizers for more than 58 years.

The content of mineral phosphorus in the soil increased with the application of phosphorus fertilizers. Therefore, with permanent cultivation, the increase in mineral phosphorus was higher and ranged from 2063 to 2098 mg·kg^{-1}. In general, mineral phosphorus content in light chestnut soil was higher than organic soil and ranged from 76.6–78.0%.

The study of the fractional composition by GINZBURG and LEBEDEVA [1971] showed that the systematic application of phosphorus fertilizers for 58 years led to an increase in the amount of "active" mineral phosphates in which the number of loose-bound ($Ca\text{-}P_I$) and different-base ($Ca\text{-}P_{II}$) calcium phosphates increased not only in absolute but also, in relative terms to gross phosphorus.

With the permanent cultivation of sugar beets, the relative decrease in high-base phosphates was 55.9 and 53.8% of the use of 4400 and 6600 kg·ha^{-1} of phosphate fertilizers. In the control and nitrogen-potassium variants, their content was 66.2 and 65.9%.

Thus, the long-term and systematic use of mineral fertilizers, particularly phosphates, increased the content of gross phosphorus in the soil in the studied crop rotations. Moreover, the proportion of mineral phosphorus in irrigated chestnut soils was higher than that of organic phosphorus. Determination of the fractional composition of mineral phosphates showed that the content of the most soluble fractions of calcium phosphates ($Ca\text{-}P_I + Ca\text{-}P_{II}$) and high-base calcium fractions ($Ca\text{–}P_{III}$) increased from the prolonged

Table 2. Effect of long-term application of fertilizers on sugar beet productivity in permanent cultivation

Treatment	The average yield of root crops ($Mg \cdot ha^{-1}$)				Sugar content (%)	
	1961–1975		2017–2019			
	average yield of root crops	increase in yield from phosphorus fertilizers	average yield of root crops	increase in yield from phosphorus fertilizers	1961–1975	2016–2018
Control	16.3	–	9.125	–	15.9	14.5
NK background	18.45	–	9.935	–	14.8	14.5
NPK	22.05	3.6	17.72	12.785	15.6	15.7
NP1.5K	22.7	4.25	18.36	13.425	16.0	15.9

Source: own study.

and systematic use of a single and one and a half norms of phosphate fertilizer. However, determining the fractional composition of mineral phosphates in autumn showed that the content of the first two fractions ($Ca\text{-}P_I$ + $Ca\text{-}P_{II}$) was decreasing. In contrast, the quantitative content of high-base calcium fractions ($Ca\text{-}P_{III}$) increased. This is because the most soluble fractions of mineral forms of phosphates were used in the process of vegetation of cultivated plants. The increase of high-base forms of mineral phosphorus forms occurred due to the transition of soluble forms of phosphorus to inaccessible forms for plants. The content of phosphates of one-and-a-half oxides (Al and Fe-P) in the studied soils was no more than 11–12% of the soil's mineral phosphates. The greatest amount of aluminium and iron phosphates were concentrated in the upper soil horizons.

The data illustrates that phosphate fertilizers show a high efficiency in the permanent sowing of sugar beet (Tab. 2). For 15 years of permanent sowing, the average yield increased from the introduction of phosphates by 3.75–4.25 $Mg \cdot ha^{-1}$ compared to the background. However, since 1973, the introduction of a one-and-a-half norm of phosphorus did not increase yield compared to the single norm. It should be noted that in comparison with 1961–1975, there was no sharp decrease in the productivity of sugar beet. Thus, in the NPK variant, the yield was 22.05 $Mg \cdot ha^{-1}$ in 1961–1975 with a sugar content of 15.6%, in 2017–2019 – 17.72 $Mg \cdot ha^{-1}$ with a sugar content of 15.7%. In the NP1.5K (one and a half dose of phosphorus) variant, the same indicator reached 22.7 $Mg \cdot ha^{-1}$ and 16%, 13.425 $Mg \cdot ha^{-1}$ and 15.9%, respectively. The longer the duration of permanent cultivation of sugar beet, the more reduced the yield of root crops.

CONCLUSIONS

A significant change in the qualitative and quantitative composition of phosphorus compounds in the soil has occurred over the last 58 years of using light chestnut soil in the permanent sowing of sugar beets. The increase in gross reserves of phosphorus during its long-term use mainly depended on the fertilizer norm. Therefore, in the control and nitrogen-potassium variants, the changes undergone were minimal, while when phosphorus fertilizers were applied, their content in the arable layer of the soil significantly increased. The annual introduction of a single norm of phosphorus (4400 $kg \cdot ha^{-1}$ a.s.) led to the increase by 2660 $mg \cdot ha^{-1}$, and when one and a half of its rates (6600 kg a.s.) was applied, it increased by 2860 $mg \cdot kg^{-1}$ of soil.

The application of phosphorus fertilizers does not contribute to the accumulation of organic phosphorus in the soil, but on the contrary, it decreases. This could be due to more intensive mineralization of organic matter in the soil monoculture.

When applying phosphorus fertilizers into the soil, the accumulation of mobile phosphorus occurs on an annual basis in stable phosphorus fertilizer rates. Thus, when applying 4400 and 6600 kg of phosphorus a.s., its content in the mobile layer increased to 36.1–50.6 mg or 1.5–2.5 times compared to the initial content and 2.1–3.5 times compared with the control confirmation.

Thus, studies have shown that the effectiveness of phosphorus fertilizers is determined by the content of mobile phosphorus and its close, immediate reserves – the sum of loose-bound and different-base calcium phosphates. The conditions of phosphorus nutrition of sugar beet depend on the availability of mobile forms of phosphorus in the soil (the degree of fertilization with phosphorus), as well as on the precursor.

Phosphorus fertilizers in soils eventually turn into less mobile forms. As a result of the systematic application of phosphorus fertilizers, phosphorus accumulates in the soil, mainly in the form of minerals and partially in the form of organic compounds. In irrigated light chestnut soils, fertilizer phosphorus, even with long-term interaction with the soil, is almost all in the composition of "active" phosphates extracted by the Ginzburg and Lebedeva method. In this case, several groups of phosphoric compounds are formed, differing in different solubility. Due to the introduction of phosphorus, loose-bound phosphates decrease with the formation of different-base and partially high-base phosphates. In the soil of crop rotation fields, the most soluble phosphates ($Ca\text{-}P_I$ + $Ca\text{-}P_{II}$) contain less than under permanent crops, which is associated with a significantly higher yield of sugar beet.

Consequently, the accumulation of mobile phosphates and phosphates of loose-bound and different-base fractions in the soil is the basis for increasing sugar beet yields. However, the soil's enrichment with phosphorus over the optimal level leads to unproductive costs and low availability of soil phosphorus. Hence, higher unproductive costs of nitrogen and potassium as a consequence of a shortage of crops.

The optimal level of mobile phosphorus in the soil content of 30–45 $mg \cdot kg^{-1}$ with the sum of loose-bound and different-base 385–445 $mg \cdot kg^{-1}$ of soil.

It should be noted that in comparison with 1961–1975, there was no sharp decrease in the productivity of sugar beet. Thus, in the NPK variant, the yield was 22.05 $Mg \cdot ha^{-1}$

in 1961–1975 with a sugar content of 15.6%, in 2017–2019 – 17.72 Mg·ha^{-1} with a sugar content of 15.7%. In the NP1.5K variant, the same indicator reached 22.7 Mg·ha^{-1} and 16%, 13.425 Mg·ha^{-1} and 15.9%, respectively. The longer the duration of permanent cultivation of sugar beets, the more the root crops decrease.

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