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THE ROLE OF PHOSPHORUS IN MODERN AGRICULTURE OF THE CHERNOZEM STEPPE OF UKRAINE

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Abstract

The article analyzes the change in the content of mobile phosphorus in the arable and subarable horizons of southern chernozem with systematic fertilization in the conditions of the Chernozem Steppe of Ukraine. Thus, the efficiency of using phosphate fertilizers is closely related to the absorption of phosphorus by the soil. If the absorption capacity is full, the additional doses of phosphorus that are supplied remain mobile and are easily used by plants. However, the absorbed phosphorus, under certain conditions, is able to pass into the soil solution, to acquire mobility. The study showed that the absolute content of mobile phosphorus increases with increasing of phosphate fertilizers doses. Its highest content (8.8 mg/100 g) was observed with the mineral system of fertilizers - the average annual increase was 0.16 mg/100 g of soil. With the systematic use of phosphate fertilizers, the following dependence is observed: the higher the rate of their application, the higher the content of mobile compounds in the soil, the lower the payback of a unit of active substance by the harvest increase and vice versa.

Key words**:** *mobile phosphorus, southern chernozem, ordinary chernozem*

INTRODUCTION

In modern conditions, it is important to develop the most beneficial from both economic and environmental points of view, methods of preserving and improving the soil fertility. One of the most important measures to maintain fertility and increase crop yields is the rational use of mineral fertilizers. However, in the recent years, due to a number of objective and subjective reasons, significantly fewer fertilizers, especially phosphate fertilizers, are applied.

Thus, over the past 25 years, the amount of phosphorus applied per hectare of arable area has decreased from 40 kg of active substance to 3-4 kg, nitrogen from 60 kg to 5-15 kg and potassium from 35 kg to 1.2 kg of active substance (a.s.). And although since 2006, the use of mineral fertilizers has gradually increased: from 2006 to 2010 - from 27.2 kg a.s./ha to 42.6, and by 2018 the average annual application has increased to 72.4 kg a.s./ha, - they remain far from scientifically-based norms and ratios [8].

Despite the prevailing trend of increasing the total number of applied fertilizers, a large proportion of their total amount is nitrogen fertilizers and the ratio N : P : K ranges from 1 : 0.17 : 0.10 to 1 : 0.26: 0.20. Therefore, the availability of the soils in the Odessa region with mobile forms of phosphorus has decreased even over the past five years compared with the previous by 4.7% [3].

The relatively low content of phosphorus in the composition of the applied mineral fertilizers reduces the effectiveness of nitrogen ones, increases the cost of means of protection against diseases [12]. Plant demand for phosphate is especially high in early periods of growth, and even excess nutrition in subsequent phases cannot compensate for its deficiency, which leads to a decrease in protein content in grains, vegetables, fruits, and root crops - sugar content, in potato starch tubers [14, 21, 23]. In this regard, the problem of using phosphorus in modern agriculture is quite acute.

Soil phosphorus is known to belong to biogenic elements and its accumulation in the humus horizon is the result of a centuries-old process of its biological transfer from deeper soil layers. The gross content of phosphates in different soils varies in a wide range (0.1-0.3%). In the arable layer of the southern chernozems under study, it contains 0.09% and, under the conditions of a long-term stationary experiment, increases to 0.13%.

In most soil types, phosphorus is found in slightly soluble mineral and organic forms inaccessible to plants. Numerous studies have shown that the accumulation of mobile phosphates is determined by a number of factors: the type of soil and its properties, the doses of fertilizers and the duration of their interaction with the soil, the hydrothermal regime, etc. [4, 7, 10, 13, 15].

Given the weak mobility of phosphorus and its negative balance in the agriculture of the black earth (chernozem) zone of the southern Steppe of Ukraine, the problem of phosphorus nutrition of plants is very relevant.

Optimization of the phosphorus regime is a significant part of the general problem of developing optimal parameters of soil quality and the main condition for the formation of stable high yields. In this regard, the study of the processes accompanying the conversion of phosphorus in chernozem has important theoretical and practical importance.

The research purpose was to study the fertilizers effect on the phosphate state of chernozems depending on the doses, combinations and regularity of their use.

To achieve the purpose, the following tasks were set:

- Identify the effects and after-effects of the systematic application of fertilizers on the phosphate state of the southern chernozems;
- Study changes in the content of soil phosphates under optimal (various) hydrothermal conditions with the application of fertilizers depending on their doses and combinations.

MATERIALS AND METHODS

The studies were carried out on the basis of a long-term stationary experience of the department of soil science, agrochemistry and organic production of the Odessa State Agricultural Experimental Station (certificate of state registration, No.80) on the southern low humus clayey-loamy chernozem.

The experience was founded in 1972; soil samples were taken in 2017 from the arable and subarable layers on the plots, where fertilizers were applied for 45 years and on the areas of the after-effect of fertilizer systems (where fertilizers were not applied for 14 years). For the model experiment, samples of the ordinary chernozem were used. A sample of the soil sample was placed in a glass container and saturated with distilled water (control variant) or fertilizer solutions.

***In the I model experiment*,** the duration of the composting was 21 days, while creating the optimal moisture and temperature: t = 28^0C, humidity - 70% of the Field Water-holding Capacity (FWC). Phosphorus and potassium were introduced in the solution form of potassium phosphate monosubstituted, and nitrogen in the solution form of ammonium nitrate at the rate of 200 kg a.s. on the 1 ha. However, in our research area, a hot, dry summer with insufficient precipitation is characteristic, that is, soil moistening alternates with drying. To recreate these conditions, we put the second model experience.

The II model experiment - composting for 90 days with periodic wetting to a humidity of 70% of the FWC and drying to an air-dry state, t = 28^0C. Creating such conditions made it possible to trace changes in the phosphate regime of the soil in conditions close to the arid conditions of the southern steppe. Phosphorus and potassium were introduced in the form of a solution of mono-substituted potassium phosphate, and nitrogen — in the form of a solution of ammonium sulphate at the rate of 400 kg a.s. on the 1 ha.

The scheme of model experiments is presented in table 1.

Table 1. Schemes of model experiments

No	Variant	Composition
The first model experience		
1/I	Control	150 g of soil + 50 ml H_2O
2/I	N = 16.33 mg/100 g of soil	150 g of soil + 50 ml solution (50 ml H_2O + 0,07 g NH_4NO_3)
3/I	N = 16.33 mg/100 g of soil P_2O_5 = 31.31 mg/100 g of soil K_2O = 20.77 mg/100 g of soil	150 g of soil + 50 ml solution (50 ml H_2O + 0,07 g NH_4NO_3 + 0,09 g KH_2PO_4
The second model experience		
1/ II	Control	150 g of soil + 50 ml H_2O
2/ II	N = 112.0 mg/100 g of soil SO_4 = 384.0 mg/100 g of soil	150 g of soil + 50 ml solution (50 ml H_2O + 0,375 g $(NH_4)_2SO_4$)
3/ II	P_2O_5 = 109.6 mg/100 g of soil K_2O = 72.7 mg/100 g of soil	150 g of soil + 50 ml solution (50 ml H_2O + 0,15 g KH_2PO_4
4/ II	N = 112.0 mg/100 g of soil SO_4 = 384.0 mg/100 g of soil P_2O_5 = 109.6 mg/100 g of soil K_2O = 72.7 mg/100 g of soil	150 g of soil + 50 ml solution (50 ml H_2O + 0,15 g KH_2PO_4 + 0,375 g $(NH_4)_2SO_4$

Source: The schematic of experimental data is taken from the authors [10, 13].

Determination of the mobile phosphorus content was carried out in an extract ammonium carbonate extraction solution, pH = 9.0, according to Machighin method [1].

RESULTS AND DISCUSSIONS

Based on a number of experiments, it has been established that the systematic use of fertilizers on all types of soil increases the total phosphorus content in the arable layer, the reserves of its accessible compounds and the availability for cultivated plants [11, 20, 22]. According to the results of the research on the background of mineral fertilizer application in the 45th year, the total phosphorus content significantly increases (after 6 field crop rotation) and even in the 14th year of the after-effect of the fertilizers applied during the previous period, the total phosphorus content in the ploughed layer exceeds the control variant (Table 2).

Consider changes in the content of mobile phosphorus in the southern chernozem with systematic long-term fertilization - 45 years (Table 3) and after the termination of their application (Table 4).

The study of the phosphate state of southern chernozems made it possible to ascertain the results of its changes over time.

Table 2. The total P_2O_5 content in the chernozem in long-term field experience on different fertilizers backgrounds (fonds)

Experience Variant	Content of total P_2O_5, %			
	Fertilizer action		Fertilizer after-effect	
	0–30 cm	30–50 cm	0–30 cm	30–50 cm
Control	0.09	0.08	0.09	0.08
Fond 1 (F1) – Manure 45 t/ha (N_{300})	0.10	0.07	0.08	0.08
F1+ $N_1P_1K_1$ $N_{300}P_{150}K_{150}$	0.10	0.10	0.10	0.07
F1+ $N_0P_1K_1$ $P_{300}K_{300}$	0.10	0.08	0.10	0.08
$N_{1,5}P_{1,5}K_{1,5}$ $N_{600}P_{300}K_{300}$	0.13	0.09	0.11	0.08

Source: Own calculation.

Table 3. The mobile P_2O_5 content in the arable and subarable horizon of southern chernozem after long-term fertilization

No	Fertilizers applied for the period of research	Soil layer, cm			
		0–30	30–50	0–30	30–50
		Content of P_2O_5, mg/100 g soil			
1	Control	1.6	0.8	± to control	
2	Manure 385 t/ha + N_{600}	2.8	0.8	1.2	0.0
3	Manure 385 t/ha + N_{1650} $P_{1240}K_{1120}$	5.8	1.7	4.2	0.9
4	Manure 385 t/ha + $P_{1540}K_{1420}$	6.0	2.4	4.4	1.6
5	N_{4360} $P_{2035}K_{1855}$	8.8	2.2	7.2	1.4

Source: Own calculation.

Table 4. The mobile P_2O_5 content in the arable and subarable horizon of southern chernozem after-effect of fertilizers

No	Fertilizers applied for the period of research	Soil layer, cm			
		0–30	30–50	0–30	30–50
		Content of P_2O_5, mg/100 g soil			
1	Control	1.6	0.8	± to control	
2	Manure 265 t/ha	2.2	1.0	0.6	0.2
3	Manure 265 t/ha + N_{1050} $P_{940}K_{820}$	4.0	1.6	2.4	0.8
4	Manure 265 t/ha + $P_{940}K_{820}$	4.0	2.2	2.4	1.4
5	N_{1675} $P_{1435}K_{1255}$	4.9	2.5	3.3	1.7

Source: Own calculation.

The mobile phosphorus content in the arable soil depends on the amount of fertilizer applied. The highest amount of phosphorus (8.8 mg/100 g) was found in the application of mineral fertilizers - the annual increase constituted 0.16 mg/100 g of soil. Hence, the content of mobile phosphorus in soil increases with the increase in phosphorus fertilizers.

After the cessation of fertilization, the concentration of mobile phosphorus sharply decreased in the arable layer of the soil. The rate of decline (mg P_2O_5 per 100 g of soil per year) on the mineral system of fertilizers was maximum and amounted to 0.279; on organic system - minimal (0.043), organic-mineral fertilizer system occupied an intermediate position (0.129). Thus, phosphorus was "lost" much faster than its accumulation occurred.

To establish the quantitative dependences of the soil phosphate content on the dose of fertilizers, laboratory experiments I and II were carried out. Under optimal conditions while maintaining 70% of moisture content from the full moisture capacity of the soil and a temperature of 28ºC, soil samples were composting and collected from different genetic horizons of ordinary chernozem with mineral fertilizers.

Research results show that the content of phosphorus mobile forms, extracted by Machighin method, in the control variant of the I model experiment decreased throughout the profile, and in the control variant of the II experience decreased in the arable horizon (Table 5).

Table 5. The content of mobile phosphorus in the model experience (control)

P_2O_5 balance in model experiments		
Sampling depth, cm	I experience (control)	II experience (control)
0-30	-1.81	-3.15
30-49	-0.54	0.06
49-64	-0.22	0.18
64-90	-0.11	0.39
90-125	-0.32	0.18
125-150	-0.32	0.38

Source: Own determination.

The same situation is noted in the variants with the introduction of nitrogen fertilizers (Table 6). A decrease in the phosphate content in soil occurs, apparently, due to their biological absorption.

The results of model experiments also showed that the optimal conditions of temperature (28^0C) and humidity (70% of the FWC) contribute to the binding of phosphates. Biological binding P_2O_5 has been pointed out more than once by both classics and scientists of subsequent generations [2, 5, 6, 17-19].

Table 6. The content of mobile phosphorus in the model experience (nitrogen fertilizers)

P_2O_5 balance in model experiments		
Sampling depth, cm	I experience (with NH_4NO_3)	II experience (with $(NH_4)_2SO_4$)
0-30	-1.59	-2.85
30-49	-0.54	0.16
49-64	-0.22	0.28
64-90	-0.11	0.59
90-125	-0.19	0.18
125-150	-0.13	0.18

Source: Own determination.

In the composition of the cells of microorganisms in large quantities are carbon, oxygen and nitrogen, in much smaller phosphorus and sulphur. Phosphorus-potassium fertilizer application into the soil enhances the activity of nitrogen-fixing microorganisms [24].

Table 7. The content of mobile phosphorus in the model experience (phosphorus-potassium fertilizers)

P_2O_5 balance in model experiments	
Sampling depth, cm	II experience (with KH_2PO_4)$^{2)}$
0-30	-44.05
30-49	-101.99
49-64	-80.92
64-90	-69.96
90-125	-73.52
125-150	-72.32

Source: Own determination.

Table 8. The content of mobile phosphorus in the model experience (complex fertilizers)

P_2O_5 balance in model experiments		
Sampling depth, cm	I experience (c KH_2PO_4 + NH_4NO_3)$^{1)}$	II experience (with KH_2PO_4 + $(NH_4)_2SO_4$)$^{2)}$
0-30	-25.41	-64.25
30-49	-30.22	-108.94
49-64	-29.99	-86.92
64-90	-29.88	-81.91
90-125	-31.63	-81.22
125-150	-31.12	-86.92

1) the difference between the content of P_2O_5 before composting (initial in soil + 31.31 mg/100 g of soil P_2O_5 of fertilizers) and after.
2) the difference between the content of P_2O_5 before composting (initial in soil + 109.6 mg/100 g of soil P_2O_5 of fertilizers) and after.

Source: According to recommendations [10].

On the variants with only phosphorus-potassium fertilizers introduction and jointly nitrogen and phosphorus-potassium fertilizers (variant P_{200} - 31.31 mg/100 g, P_{400} - 109.6 mg/100 g of soil) after 30 and 90 days of soil composting the content of phosphorus mobile forms turned out to be lower than calculated (Table 7 and 8).

According to the results of the laboratory experiment, we established a high correlative dependence of the content of nitrate nitrogen on the presence of mobile phosphates and potassium in the soil, which is emphasized by the correlation coefficients obtained by us for

$r_{P_2O_5} = -0.552$ at $t_{r\,P_2O_5} = 4.28$ and

$r_{K_2O} = -0.532$ at $t_{r\,K_2O} = 4.08$.

The results indicate antagonism of nitrates and phosphates, nitrates and potassium, which is consistent with data from other researchers [9, 16]. One of the reasons for the antagonism of accessible phosphates and nitrates noted by Lebyadintsev [9] lies in the fact that in the composting process phosphorus is bound by nitrification bacteria producing nitrates. Phosphate fertilizers applied into the soil during composting increased by 28–61% the content of mobile phosphorus in the arable layer (Table 9).

Table 9. The mobile phosphorus accumulation in soil of model experiments with fertilizers use, %

Sampling depth, cm	I model experience	II model experience	
	with $KH_2PO_4 + NH_4NO_3$	with $KH_2PO_4 + (NH_4)_2SO_4$	with KH_2PO_4
0-30	28	43	61
30-49	5	1	7
49-64	5	21	26
64-90	5	25	36
90-125	0	26	33
125-150	2	21	34

Source: Own determination.

When only phosphorus-potassium fertilizers are applied during composting, the greatest increase in mobile phosphates is obtained. At the same time, 61% of the total amount of mineral phosphates was found in the arable horizon, i.e., more than half of the phosphorus of fertilizers in chernozem during composting for 90 days is found in the form of mineral phosphates.

The content of phosphorus mobile forms in the soil depends on many factors, including its level, which is associated with different biota activity. So, when the soil dries out, the content of phosphorus mobile forms decreases, and after wetting it tends to increase. This pattern is observed when soil moistening alternates with drying periods (II model experiment), when soil dries out, and the availability of phosphorus decreases due to the rapid formation of insoluble anion complexes (PO_4^{3-}, HPO_4^{2-}, H_2PO^{4-}) with cations (CaO, Fe, Al and others) and due to its inclusion in organic compounds by microorganisms.

Studies have shown that the most intense accumulation of mobile forms of phosphorus occurred in the first experiment with composting for 21 days under optimal conditions. The utilization rate of phosphorus from mineral fertilizers of the arable horizon in the first model experiment is 28%, whereas in the second experiment, with changing conditions and an increase in the duration of composting, its proportional increase was not observed.

In order to find the reasons for the seasonal variability of the P_2O_5 mobility, we carried out another model experiment: the soil samples were composted at optimum humidity (70% of the FWC) and temperature (28^0C) for 14 days. To suppress microbiological activity, a few drops of toluene were introduced into a portion of compostable soil (Table 10).

Table 10. The composting effect on the mobile phosphates content in southern chernozem

Symbols and their meanings	Before compos-ting - X_1	After compos-ting - X_2	After composting with toluene - X_3	X_1-X_2	X_2-X_3
P_2O_5 in mg per 100 g of soil	3.1	1.9	3.2	1.2	1.3
	18	12	12	-	-
	0.52	0.36	0.47	-	-
$*t_{0,05} = 2,07$	-	-	-	2.25	2.34

Source: Own determination.

From table 10 it can be seen that in the case when the soil sample is placed under normal conditions, the mobility of phosphates is significantly reduced. If composting was carried out under sterile conditions, it did not affect the amount of mobile P_2O_5. Consequently, a significant decrease in phosphate mobility in soil in the spring months is most likely due to the fact that in this time the optimum conditions for active microbiological activity are created in the soils. Summer samples are characterized by a lower content of mobile forms of P_2O_5 due to the lack of atmospheric moisture.

An analysis of the correlative relationship between the productivity of winter wheat with fertilizer doses confirms [12] the crucial role in optimizing its nutrition - balancing nitrogen with phosphorus (Table 11).

Table 11. Effect of fertilizer rates on root rots infestation and winter wheat harvest

Factors that influence	The number of affected plants	Cumulative disease progression	Number of plants per m^2	Productive tillering	Harvest
The number of affected plants	–	–	–	–	- 0.087
Cumulative disease progression	–	–	–	–	+ 0.330
Number of plants per m^2	–	–	–	–	- 0.350
Productive tillering	–	–	–	–	+ 0.212
Nitrogen dose	+ 0.314	+ 0.298	+ 0.076	- 0.033	+ 0.421
Phosphorus dose	- 0.216	+ 0.100	- 0.068	+ 0.357	+ 0.748
Potassium dose	+ 0.111	+ 0.060	+ 0.104	+ 0.319	+ 0.310
Total amount of fertilizer	0.000	+ 0.070	- 0.054	+ 0.094	+ 0.465
(Required value $r_{0.5}$ ± 0.46)					

Source: Own determination.

With the required value $r_{0.5}$, the actual indicator of the relationship of phosphorus doses with the yield was +0.748, and total fertilizers with the exception of phosphorus +0.465. As the research results showed, the connection between the winter wheat yield and the nitrogen doses only approaches the reliable one (+0.421) As is known, the total phosphorus content in plants depends on the level of phosphate nutrition, the phase of plant development, the degree of provision with other elements. As a result of the statistical processing of empirical data (correlation and regression analysis), a model of dependence of the P_2O_5 content in soils (Machighin's method) on the variation of phosphorus in plants (leaf diagnosis by Tzerling) was obtained (Fig.1).

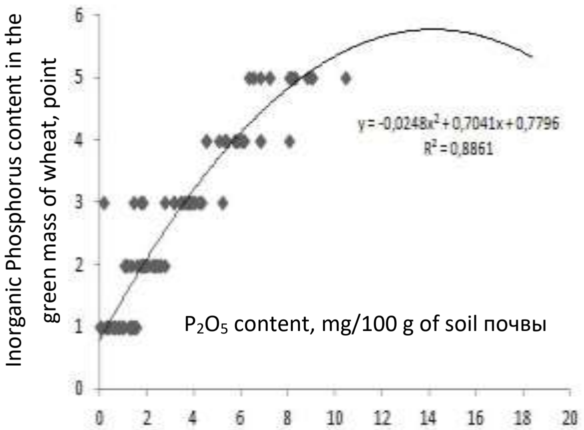

Fig. 1. The dependence of the P_2O_5 content in the green mass of winter wheat on the mobile phosphorus content in the arable layer of southern chernozem
Source: Own determination.

Step-by-step analysis by enumerating mathematical functions from a linear pair to nonlinear and graphical analysis made it possible to choose the second order parabola as the most reliably reflecting the above dependence at the 95% probability level, the general form of which is described by equation (1):

$$Y_x = a_0 + a_1X + a_2 X^2 \quad (1).$$

In the case of the dependency we are investigating, based on the 93 observations made and using the Excel program in the calculations of the Regression function, the equation (2) is obtained:

$$Y_x = 1.7796 + 0.7041X - 0.0248X^2, \quad (2),$$

where:

Y_x – the content of P_2O_5 in the green mass of wheat, points;

X – the content of P_2O_5 according to Machighin, mg/100 g of soil.

Regression analysis confirms the presence of a very high correlation between the variation of the effective and factorial signs (according to the Cheddock scale). The preference of the parabolic function in comparison with the linear function was given on the basis of a comparison of the coefficients of determination R^2. In the case of a linear dependence, R^2 was 0.871, in the case of a parabolic dependence, R^2 = 0.886. This indicates that the parabolic function more adequately reflects the dependence between the studied traits and in this case almost 89% of the variation of the phosphorus content in the plant juice depends on the variation of its content in the soil.

The data is reliable at a given level of significance of 0.05, which corresponds to the 95% level of probability. The calculated value of the F-criterion significantly exceeds its critical (tabular) value, which confirms the hypothesis on phosphorus content in soils and plants. The data obtained showed that there is a great dependence on the variation between P_2O_5 content in soils and the phosphorus intake in plants.

Table 12. Payback dependence of the phosphate fertilizers on the dose of their application (kg of grain per 1 kg a.s. of phosphorus). Data from the stationary field experiences, average for 1972-2008.

Dose of phosphate fertilizers, kg/ha	Winter wheat predecessor			Corn for grain
	Black steam	Peas	Corn	
60	1.1	5.7	3.7	5.8
40	2.8	7.8	4.1	6.3
20	3.8	10.6	15.7	27.0
Crop	Peas	Sunflower on the after-effect of fertilizers		
30	1.7	Contributed during crop rotation, kg/ha		
20	7.4	330	210	110
10	28.5	0.18	0.72	1.24

Source: Own calculation.

In the model experiments, the 93 observations were made with phosphorus content in the soil from 0.0 to 10.4 mg/100 g. In the observation process it was established that, when the mobile phosphorus content increased from 0.0 to 14.0 mg in soil, increases its content in plant juice. Additional increase of the mobile phosphorus content in the soil more than 14.0 mg decreases the efficiency of its absorption.

According to the results of production experience only on the variant with mineral fertilizer system (P_{60}), the calculated provision of winter wheat with phosphorus due to its reserves in southern chernozems corresponds to its high content in the juice of plants.

The results of production experience with applying of different doses of phosphate fertilizers and the obtained parabolic function confirm that the studied soils require the introduction of phosphate fertilizers and their phosphate regime regulation.

CONCLUSIONS

The study of the changes direction occurring in the soil under the fertilizers influence, allows adjusting the nutritive regime of plants, to develop measures of influence on the processes occurring in the soil and in plants in order to increase soil fertility, harvest and improve its quality. It is possible to restore the content of phosphorus available for plants in the soil by applying mineral fertilizers. With the systematic use of phosphate fertilizers, this dependence is observed: the higher the rate of their application, the higher the content of mobile compounds in the soil, the lower the return on the unit of the active substance by the yield increase and vice versa

After the termination of fertilization, the concentration of mobile phosphorus sharply decreased in the arable layer of soil. The rate of decline (mg P_2O_5 per 100 g of soil per year) on the mineral system of fertilizers was maximum and amounted to 0.279; on organic - minimal (0.043), organic-mineral fertilizer system occupied an intermediate position (0.129).

Conducting research in a model laboratory experiment with the creation of specified phosphate levels confirm the data obtained in the field. According to the results of the laboratory experiment, was established a high correlative dependence of the content of nitrate nitrogen on the presence of mobile phosphates and potassium in the soil, which is emphasized by the correlation coefficients obtained for:

$r_{P_2O_5} = -0.552$ at $t_{r\,P_2O_5} = 4.28$ and

$r_{K_2O} = -0.532$ at $t_{r\,K_2O} = 4.08$.

The results of production experience on the application of different doses of phosphate fertilizers and the obtained parabolic function of the dependence of the P_2O_5 content in the green mass of wheat on the content of mobile phosphorus (according to Machighin method) and the correlative relationship between the state and productivity of winter wheat with doses of fertilizers confirm that to obtain high yields with high quality the black soil of the Ukraine Steppes require the application of the phosphate fertilizers and the regulation of their phosphate regime.

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