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AGROCHEMISTRY. SOIL SCIENCE

Productivity Models of Grain Crop Rotation on Gray Forest Soils of the Upper Volga Region

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Abstract—The influence of fertilizers on grain crop rotation productivity and dynamics of ammonium and nitrate nitrogen reserves has been studied in a field experiment on the gray forest soils of the Upper Volga region to develop crop rotation productivity management models. Organic fertilizers have included cattle, chicken, and goose manure and have been applied in various doses. The experimental design has included variants of applying mineral fertilizers (NPK) and their combination with NK and organic fertilizers. It has been established that more than 90% of crop rotation productivity variations accrue to nitrogen in organic and mineral fertilizers; in the light of their interaction, this figure rises to 96.8%. A close power-law or hyperbolical relation has been discovered between the average crop rotation productivity and the average annual nitrate nitrogen reserves in the early crop vegetation. The same kind of relation for this period has been discovered between the first parameter and the ammonium and nitrate nitrogen reserves in the soil solution (mobile nitrogen stock). It is proposed to estimate the mobile nitrogen stock by the mobilization nitrogen pool that depends on the dose of nitrogen in mineral and organic fertilizers.

Keywords: gray forest soil, organic and mineral fertilizers, crop rotation productivity, ammonium and nitrate nitrogen reserves, regression equations

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INTRODUCTION

Efficient application of fertilizers in science-based crop rotations is a major factor of improving farming crop capacity and product quality in a sufficiently moistened zone, including the gray forest soils of the Upper Volga region [1, 2]. However, Russia has exported the greater share (85–89%) of mineral fertilizers produced at chemical plants over the years. In recent years, the national AIC has had only 1.9–2.6 million deadweight tons at its disposal out of the entire amount (17.8–18.3 million deadweight tons) of mineral fertilizers produced in Russia, whereas the domestic supplies of mineral fertilizers reached 9.9 million deadweight tons (61% of the total output) in 1990. The share of nitrogen in fertilizers has risen to 60% as compared with 41% in 1986–1990 [1].

The cattle, pig, sheep, and goat stock has dropped by 200, 100, 150, and 150%, respectively [3], since 1990, which has led to a decline in dairy and meat production and reduced the output and field-applied amount of manure from 3.5 to 1.1 t/ha. In 2013–2014, the fowl-to-cattle stock ratio was by 150% higher than in 1990, which meant a significantly higher share of fowl manure in organic fertilizer output, and this made it necessary to elaborate efficient ways of using that manure.

It is known [1] that nitrogen is the main nutrient that limits grain crop capacity on both the soddy podzols of the Central Federal District and the soils in the forest steppe zone. A concept model of predicting the efficiency of nitrogen fertilizers applied in cultivating fall rye on the soddy podzols of the southern taiga forest zone has been elaborated on the basis of 148 field experiments. To this end, the researchers used the mobile phosphorus and exchange potassium content in the soil and the nitrogen fertilizer doses commonly applied in experiments of the Geographical Network and Agrochemical Service of Russia. In that model, nitrogen fertilizers became less efficient with an increasing dose of nitrogen and more efficient with an increasing soil supply of phosphorus and exchange potassium.

The purpose of the studies based on work [2] was to elucidate the influence of fertilizers on the capacity of cultivated grain rotation crops and the dynamics of the ammonium and nitrate nitrogen reserves on the gray forest soils of the Upper Volga region for elaborating crop rotation productivity management models.

Table 1. Crop capacity and crop rotation productivity, hwt. grain units/ha

Variant, dose, t/ha	Winter wheat in 2012	Barley in 2013	Oats in 2014	Vetch-oats mixture in 2015	Winter wheat in 2016	Oats in 2017	Average crop rotation productivity
1. Reference variant	47.0	18.0	28.0	16.2	38.4	27.4	29.1
2. $N_{40}P_{40}K_{40}$	55.6	25.4	38.0	21.8	62.2	30.6	38.9
3. $2N_{40}P_{40}K_{40}$	53.8	27.4	41.4	23.2	70.6	35.0	41.9
4. Manure (28)	51.0	23.3	31.3	16.6	47.7	27.9	33.0
5. Manure (28) + $N_{40}P_{40}K_{40}$	53.3	28.5	38.1	21.9	59.2	32.5	38.9
6. Manure (14) + $N_{40}P_{40}K_{40}$	53.3	27.2	35.4	21.4	60.4	31.6	38.2
7. Chicken manure (29)	51.5	22.7	31.7	16.5	46.6	27.7	32.8
8. Chicken manure (29) + $N_{40}K_{40}$	53.0	28.2	37.4	22.1	62.0	33.7	39.4
9. Chicken manure (15) + $N_{40}P_{40}K_{40}$	54.3	28.5	36.8	21.2	64.0	33.0	39.7
10. Goose manure (50)	55.2	20.8	31.7	16.6	54.8	31.9	35.2
11. Goose manure (50) + $N_{40}K_{40}$	52.7	25.1	39.4	21.6	64.9	33.1	39.4
HCP_{05}, hwt. grain units/ha	3.7	2.2	3.2	2.1	3.9	2.2	2.9

METHODS

The studies were conducted in the experiment launched on the gray forest middle loamy soils of the Vladimir Opolie in 2011 [4]. The experiment was repeated four times. Cattle, chicken, and goose manure was used as organic fertilizers. Their doses were calculated proceeding from the application of 200 and 100 kg of nitrogen per hectare. The applied amounts for the full dose and the half-dose of nitrogen were 28 and 14 t/ha of cattle manure, 29 and 15 t/ha of chicken manure, and 50 t/ha of goose manure (200 kg of N per ha). The experimental arrangement (Table 1) also included variants of mineral fertilizers (NPK) and the combinations of NPK and NK with organic fertilizers. The reference variant contained no fertilizers.

The studies were conducted in the crop rotation with the following succession of field crops: winter wheat–barley–oats–one-year herbs (vetch-oats mixture)–winter wheat–oats. The experiment was launched in complete (pure) fallow.

The experiment involved using ammonium nitrate, superphosphate, and potassium salt. The organic fertilizers for winter wheat were applied in complete fallow for tillage, the phosphorus potassium fertilizers were applied for primary soil cultivation, and the nitrogen fertilizers were applied in spring to the feeding of growing winter wheat and for cultivation before the seeding of barley, oats, and one-year herbs. The mineral fertilizers were applied on an annual basis (except for 2017), and the organic fertilizers were applied in complete fallow. The aftereffects of the fertilizers were studied in subsequent years.

The samples of soil and plants were taken, prepared, and analyzed by general agrochemical techniques [5]. The data were statistically processed in STAT VIUA and Excel.

RESULTS AND DISCUSSION

In the years when the study was conducted (2011–2017), the precipitation regime was quite favorable. The amount of precipitates was very uneven: they varied from 39 to 139 mm (by 260%) from the second decade of September to the third decade of October, the variation was from 184 to 284 mm (by 60%) in winter and early spring, and the variation was from 285 to 431 mm (by 50%) in the vegetation phase. The application of fertilizers in the crop rotation made possible a more efficient use (by 25%) of absorbed moisture to grow a unit of production, including increased moisture consumption by the subsurface layers.

When the full mineral fertilizer and the combination of organic fertilizers with NPK and NK (Table 1) were applied, the capacity of the cultivated crops and the crop rotation productivity (in grain units) increased much higher than in the reference variant. The application of organic fertilizers alone was not so efficient.

According to equation (1), more than 90% of variations in the crop rotation productivity by linear connection (y, hwt. grain unit/ha) falls to the annual application of nitrogen in organic (x_1, kg/ha) and mineral (x_2, kg/ha) fertilizers. In the light of their interaction and quadratic dependence, this figure is even higher and reaches 96.8% (equation 2):

$$y = 30.7 + 0.0834x_1 + 0.184x_2, \quad n = 11, \quad r = 0.951, \quad r^2 = 0.905, \tag{1}$$

confidence range = 2.7 hwt. grain units/ha;

Table 2. Average annual reserves of ammonium and nitrate nitrogen (kg/ha) in the soil layer of 0–40 cm during the vegetation of crops

Variant	Early vegetation	Middle vegetation	Postharvesting	Change in reserves in the middle of vegetation compared to the early vegetation
Nitrate nitrogen reserves				
1	38.1	19.4	24.2	18.7
2	93.0	27.9	30.6	65.1
3	124	38.3	46.0	85.7
4	52.5	22.5	29.6	30.0
5	96.6	24.2	29.9	72.4
6	93.6	23.9	28.5	69.7
7	41.7	18.2	29.9	23.5
8	99.6	26.8	35.4	72.8
9	96.4	27.8	33.3	68.6
10	49.5	22.3	29.7	27.2
11	102.3	38.3	35.0	63.0
Ammonium nitrogen reserves				
1	56.6	54.9	69.8	1.7
2	63.0	57.4	74.2	5.6
3	71.0	57.0	63.3	14.0
4	58.1	54.5	64.8	3.6
5	59.4	50.2	60.8	9.2
6	62.5	52.7	60.3	9.8
7	56.1	49.9	53.7	6.2
8	62.7	51.9	54.2	10.8
9	64.2	50.2	55.6	14.0
10	57.5	50.9	58.0	6.6
11	67.2	57.7	70.8	9.5

$$y = 29.1 + 0.137x_1 + 0.392x_2 - 0.0030x_2^2 - 0.0038x_1x_2, \quad (2)$$
$$n = 11, \quad r = 0.984, \quad r^2 = 0.968,$$

confidence range = 1.8 hwt. grain units/ha.

The nitrogen in organic fertilizers was less efficient per rotation than the nitrogen in mineral fertilizers (the equivalent of mineral fertilizers for the nitrogen in organic fertilizers is abbreviated as EMF [6]) and, with the linear dependence applied, amounted to 45.3% (0.0834 × 100/0.184 = 45.3). On the whole, this comports with the poorer payback of organic fertilizer nutrients [2] on the gray forest soils of the upper Volga region. Taking into account the interaction of factors at a quadratic dependence, the efficiency of the nitrogen in organic fertilizers as compared with mineral fertilizers went down to 42%.

Since the influence of fertilizers, mainly nitrogen ones, on the capacity of cultivated crops and the crop rotation productivity (equations 1 and 2) manifests in the content and reserves of nutrients in the soil, the behavior of ammonium and nitrate nitrogen was analyzed by vegetation and across the years. The average annual dynamics of the ammonium and nitrate nitrogen reserves in the early vegetation, earing (heading of panicles), and after crop harvesting in 2012–2017 is given in Table 2.

By the middle of vegetation, the nitrate nitrogen reserves significantly decreased in all the variants. Their average 6-year drop in the phase of earing (heading of particles) in the reference variant and in the variants with organic, organic mineral, and mineral fertilizers was down to 18–22, 24–38, and 28–38 kg/ha, respectively. A minor growth in the reserves of $N\text{-}NO_3$ was observed by the beginning of harvesting as compared with the middle of vegetation. Their further reduction was observed in rainless fall.

A close power-law relation has been established between the average crop rotation productivity (y, hwt. grain units/ha) and the average annual nitrate nitrogen reserves in the soil layer of 0–40 cm in the early vege-

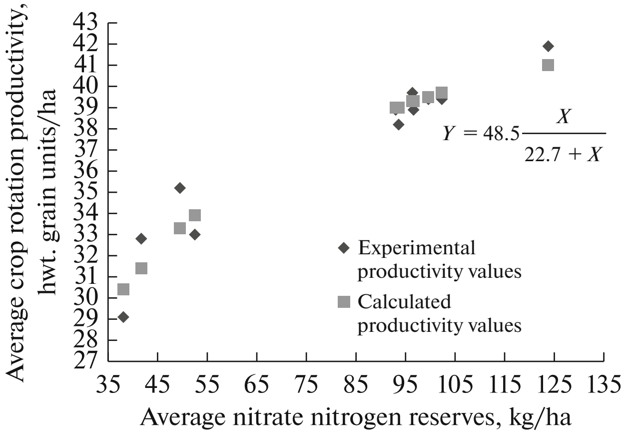

Fig. 1. Average crop rotation productivity related to nitrate nitrogen reserves in the soil layer of 0–40 cm in the early vegetation period.

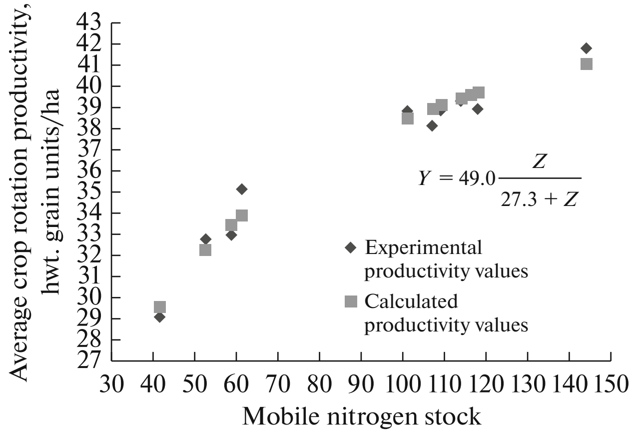

Fig. 2. Average crop rotation productivity related to mobile nitrogen stock.

tation (x, kg/ha; $38.1 < x < 124$) (equation 3). This relation was found by logarithmation, or a hyperbolical dependence (equation 4, Fig. 1):

$$\log y = 1.4225 + 0.0957\log(x - 35),$$
$$r = 0.972, \quad r^2 = 0.946,$$
$$\text{confidence range log} = 0.0235;$$
$$\text{confidence range} = 1.1 \text{ hwt. grain units/ha},$$
$$y = 26.4(x - 35)^{0.096}, \tag{3}$$
$$y = 48.5\frac{x}{22.7 + x}, \quad r^2 = 0.994. \tag{4}$$

A close power-law relation has also been established between the productivity of the cultivated crop and the reduction in the reserves of N-NO_3 from the phase of sprouts to the middle of vegetation (Δx, kg/ha; $18.7 < \Delta x < 85.5$):

$$\log y = 1.408 + 0.109\log(\Delta x - 15),$$
$$r = 0.975, \quad r^2 = 0.951,$$
$$\text{confidence range log} = 0.0223;$$
$$\text{confidence range} = 1 \text{ hwt. grain units/ha},$$
$$y = 25.6(\Delta x - 15)^{0.109}. \tag{5}$$

This reduction in the reserves occurred mainly when the plants absorbed nitrates. For example, according to work [7], the intensity of denitrification in the layer of 0–60 cm of heavy soils (leached black earth) varied from 9 to 16% and rose with depth.

There have been no major changes in the dynamics of the ammonium nitrogen reserves by the vegetation periods (Table 2). Depending on the system of fertilization, their calculated reduction in the second monitoring period as compared with the first period ranged from 2 to 14 kg/ha. After the harvesting, the reserves of N-NH_4 as compared with the second period rose again.

The mobile nitrogen stock (z, kg/ha) was calculated on the basis of the ammonium and nitrate nitrogen reserves (Table 2) in the soil layer of 0–40 cm. That stock was the sum of the ammonium and nitrate nitrogen reserves in the gray forest soil solution in the early period of crop vegetation (Table 3) [2]. The big differences in the usage coefficients of the ammonium and nitrate nitrogen reserves were caused by the fact that nitrate nitrogen was fully in a liquid phase, whereas ammonium nitrogen was only partially in a liquid phase. With the decreasing liquid-phase concentration of those nitrogen forms, especially nitrate nitrogen, the usage coefficients of their reserves decreased as well.

The established close power-law (equation 6) and hyperbolic (Fig. 2) relations of the average crop rotation productivity (y, hwt. grain units/ha) to the mobile nitrogen stock (z, kg/ha) similar to the relations of the first parameter to the nitrate nitrogen reserves discovered in the early vegetation are recorded as

$$\log y = 1.4315 + 0.0865\log(z - 40),$$
$$r = 0.973, \quad r^2 = 0.946,$$
$$\text{confidence range log} = 0.0235,$$
$$\text{confidence range} = 1.1 \text{ hwt. grain units/ha}$$
$$y = 27.0(z - 40)^{0.0865} \quad (41.6 < z < 144). \tag{6}$$

The coefficient of determination by hyperbolical relation (r^2) was 0.997; the confidence range was 1.2 hwt. grain units/ha.

The payback of 1 kg of nitrogen from organic fertilizers by adding the average crop rotation productivity (equation 1) and the related accumulation of nitrate nitrogen in the soil (variants 4, 7, and 10 compared with variant 2 in Tables 2 and 3) is nearly twice as low as the payout of nitrogen from mineral fertilizers. That is why it can be assumed that the mobilizing role of nitrogen from organic fertilizers in the accumulation

Table 3. Average annual ammonium and nitrate nitrogen reserves (kg/ha) in the soil solution in the layer of 0–40 cm in the early vegetation and their use until the middle of vegetation

Variant	Reserves $N\text{-}NO_3$	Reserves $N\text{-}NH_4$	Mobile nitrogen stock (MN)	Share of $N\text{-}NO_3$ in MN, %	Share of reserves used in the early vegetation in the layer of 0–40 cm, %	
					$N\text{-}NO_3$	$N\text{-}NH_4$
1	38.1	3.5	41.6	92	49.1	3.0
2	93.0	8.0	101	92	70.0	8.9
3	123.8	20.3	144	86	69.1	19.7
4	52.5	6.3	58.8	89	57.1	6.2
5	96.6	12.3	109	89	75.0	15.5
6	93.6	13.2	107	88	74.5	15.7
7	41.7	11.0	52.7	79	56.4	11.0
8	99.6	14.8	114	87	73.1	17.2
9	96.4	19.7	116	83	71.2	21.8
10	49.5	12.0	61.5	80	55.0	11.5
11	102.3	15.2	118	87	62.6	14.1

of nitrate nitrogen in the soil is nearly twice as weak as the role of nitrogen from mineral fertilizers. With that in mind, it was suggested to estimate the mobilizing effect of nitrogen from fertilizers on the accumulation of $N\text{-}NO_3$ in the soil at the cultivation of grain crops by equation 7:

$$S_N = D_{Nm} + 0.5 D_{No}, \quad (7)$$

where S_N is the average annual mobilizing nitrogen stock that speeds up the conversion of nitrogen in the soil to the nitrate form, kg/ha; D_{Nm} and D_{No} are the average annual doses of nitrogen from mineral and organic fertilizers, respectively, kg/ha. Similar results are presented in work [2].

The close established linear relation between the mobilizing stock of nitrogen from fertilizers (S_N), on the one hand, and the mobile nitrogen stock (z_N) and the average nitrate nitrogen reserves in the early vegetation period for 6 years (x), on the other hand, is found as

$$z_N = 36.3 + 1.63 S_N, \quad n = 11, \quad r^2 = 0.954, \quad (8)$$

$$x = 31.2 + 1.42 S_N, \quad n = 11, \quad r^2 = 0.935. \quad (9)$$

The good agreement of the actual with the calculated average annual crop rotation productivity found using the values of z_N from equation 8 according to power-law relation equation 6 has proven the great importance of the ammonium and nitrate nitrogen reserves in the gray forest soil solution to the nutrition of cultivated crops of grain crop rotation. The elaborated models will make it possible to manage the crop rotation productivity.

REFERENCES

1. Sychev, V.G. and Shafran, S.A., *Agrokhimicheskie svoistva pochv i effektivnost' mineral'nykh udobrenii* (Agrochemical Properties of Soils and Efficiency of Mineral Fertilizers), Moscow: VNIIA, 2013.
2. Okorkov, V.V., Fenova, O.A., and Okorkova, L.A., *Priemy kompleksnogo ispol'zovaniya sredstv khimizatsii v sevooborote na serykh lesnykh pochvakh Verkhnevolzh'ya v agrotekhnologiyakh razlichnoi intensivnosti* (Methods for the Comprehensive Use of Chemicalization Tools in Crop Rotation on Gray Forest Soils of the Upper Volga Region in Agro-Technologies of Various Intensity), Ivanovo: PresSto, 2017.
3. Il'in, L.I., Bausov, A.M., and Nenaidenko, G.N., A fertilizer application system as an important factor of food independence, in *Sistemy intensifikatsii zemledeliya kak osnova innovatsionnoi modernizatsii agrarnogo proizvodstva* (Systems of Agricultural Intensification as a Basis for Innovative Modernization of Agricultural Production), Suzdal: Vladimirskii NIISKh, 2016, pp. 3–16.
4. Okorkov, V.V. and Semin, I.V., Efficiency of fertilizer systems in the link of crop rotation on gray forest soil of the Vladimir Opolye, *Agrokhim. Vestn.,* 2015, vol. 1, no. 1, pp. 18–21.
5. Kidin, V.V., Deryugin, I.P., Kobzarenko, V.I., et al., *Praktikum po agrokhimii* (Practical Guide for Agrochemistry), Kidin, V.V., Ed., Moscow: KolosS, 2008.
6. *Metodika razrabotki rekomendatsii po primeneniyu udobrenii s pomoshch'yu EVM* (Methodology for Developing Recommendations for Fertilizer Application Using Computers), Moscow: VIUA, 1990.
7. Prasolova, A.A., Effect of fertilizer nitrogen on the gas regime of different soil horizons, *Extended Abstract of Cand. Sci. (Biol.) Dissertation,* Moscow: Moscow Timiryazev Agricultural Academy, 2015.

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