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AGRICULTURAL SOIL SCIENCE AND AGROECOLOGY

Transformation of Agrosoddy-Podzolic Soil Underwent Hidden Degradation under Accelerated Fertility Reproduction

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Abstract—A stationary field experiment was performed at the Men'kov branch of the Agrophysical Institute in 2006–2018 to study the impact of accelerated cultivation on the complex of properties of medium-cultivated agrosoddy-podzolic soil and on the productivity of crop rotations of different intensity. The scheme included the following variants: medium, good, and high soil cultivation (factor A); medium (NPK 1: 112 kg/ha in the field crop rotation and 205 kg/ha in the vegetable–forage crop rotation) and increased (NPK 2: 180 kg/ha in the field crop rotation and 310 kg/ha in the vegetable–forage crop rotation) rate of applied mineral fertilizers (factor B); and field and vegetable–forage crop rotation (factor C). Soil characteristics prior to the experiment were the following: the pH_{KCl} was 5.6–6.4, the organic matter content was 2.99–3.89%, and the amount of mobile phosphates and potassium (according to Kirsanov) was 296–434 and 229–720 mg/kg, respectively. The transformation of soil properties was studied by the comparative genetic method in a series of soil pits. Intensive expanded fertility reproduction resulted in a decrease in soil density by 0.10 and 0.13 g/cm^3 and in an increase in field moisture capacity by 3.8 and 5.9%, in the fraction of agronomically valuable aggregates by 13.5 and 23.6%, in pH by 0.55 and 0.58 units, in the content of carbon of organic matter by 0.42 and 0.52 %, in mobile phosphorus compounds by 53 and 138, and in mobile potassium compounds by 254 and 492 mg/kg in well- and strong-cultivated soils, respectively, by the end of the experiment. The direct consequence of the complex optimization of the nutrient regime of sandy loamy agrosoddy-podzolic soil consisted in an increase in the productivity of field and vegetable–forage crop rotations by 34–107% relative to the absolute control, and the cost efficiency of the use of mineral fertilizers was 85–284%.

Keywords: agrosoddy-podzolic soil, fertility, cultivation, mineral fertilizer system, efficiency

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INTRODUCTION

Approximately 20% of the area of arable soddy-podzolic soils in the northwestern region was brought to the status of good cultivation by the end of the 1980s due to efforts of the state and farmers [1, 2]. The formation of such soils required large expenditures and was the result of a significant transformation of soil-forming processes [2–4]. The optimization of particular soil properties and regimes was determined by a combination of factors: soil genetic features and buffering; specific climatic conditions and reclamation effect; and the intensity of farming systems, crop rotations, and fertilizer application [4–6].

Forced improper use of fertilizers under conditions of a prolonged economic crisis resulted in hidden degradation of most previously well-cultivated soils by way of agro-depletion [7–9], and their resources decreased three times [2]. The effective fertility of such soils dropped even on fallows [10–12]. The consequences of global climate change also played a negative role: a 10–15% increase in heat and moisture supply in the region caused greater productive and unproductive losses of mineral elements [13].

The results of long-term experimental studies have shown that intensive crop rotations with a productivity of 6000–9000 grain units/ha on well-cultivated soddy-podzolic soils with controlled water regime require special attention to preservation of optimal conditions, of acid-base and potash status in particular [14–16]. On this background, fertilizer systems regain the status of one of the main system-forming factors of modern adaptive agriculture along with land reclamation [17–19].

In recent years, almost all agricultural enterprises in the region, participants of the State Program of effective involvement in the turnover of agricultural lands and of the development of the reclamation complex of the Russian Federation in particular, have faced the need to quickly restore the lost soil fertility [10, 12, 13]. There is a necessary resource base of local ameliorants and organic and mineral fertilizers for the practical solution of this problem in a number of oblasts [20–22]. However, the accelerated reproduction of fertility of previously cultivated and now slight- and medium-cultivated agrosoddy-podzolic soils has not been comprehensively assessed.

The aim of this work is to study the impact of accelerated cultivation based on intensive and hyperintensive use of organic and mineral fertilizers on the complex of properties of medium-cultivated agrosoddy-podzolic soil and on the productivity of crop rotations of different intensity.

METHODS

The research method was based on a long-term field experiment laid at the Men'kov Branch of the Agrophysical Research Institute in 2006–2018. The experimental field was located on a lacustrine-glacial plain with agrosoddy slightly podzolic sandy loamy soil on two-member deposits (a thin moraine underlain by lacustrine-glacial sand from a depth of 112–125 cm). According to the agrochemical survey of 1990, the plow layer of soil was characterized by the following parameters: pH_{KCl} was 6.8, the organic matter content was 4.08%, and the amount of mobile compounds of phosphorus and potassium according to Kirsanov was 490 and 327 mg/kg, respectively. By the start of the experiment, these parameters decreased to 5.6, 2.99%, 296 mg/kg, and 229 mg/kg, respectively.

Accelerated reproduction of the fertility of this soil to good and high cultivation rate was performed during 3-year test sowing of annual grasses (2003–2005) with the application of 1 or 3 t of dolomite powder and of 220 or 540 t of bedding manure of cattle per 1 ha. By 2006, the parameters averaged 3.54% of organic matter, 349 mg/kg of P_2O_5, 482 mg/kg of K20, and 6.2 units of pH_{KCl} in well-cultivated soil and 3.89%, 434 mg/kg, 720 mg/kg, and 6.4 units, respectively, in high-cultivated soil.

Field (barley—perennial herbs—winter rye—potatoes—annual herbs) and vegetable—forage (potatoes—winter wheat—blue lupine—table beet—white cabbage—barley) crop rotations were introduced on the experimental field. To maintain the appropriate cultivation rate, we additionally applied 40 t/ha of manure once in the first rotation and 35 t/ha of poultry manure once in the second rotation to well-cultivated soil and 80 and 70 t/ha, respectively, to high-cultivated soil.

The scheme of the experiment included the following variants: medium-, well-, and high-cultivated soil (factor A); moderate (NPK 1: 112 kg/ha in the field and 205 kg/ha in the vegetable—forage crop rotation) and increased (NPK 2: 180 kg/ha in the field and 310 kg/ha in the vegetable—forage crop rotation) rates of applied mineral fertilizers (factor B); and field and vegetable—forage crop rotation (factor C). Crop-specific rates of fertilizers were determined with account for nutritional needs of crops and the planned accumulation of photosynthetically active radiation, coming to the surface in the amount from 1.5–2.0 to 3.5–4.0%.

The transformation of soil-forming processes during fertility reproduction in degraded soddy-podzolic soil was studied by the comparative genetic method in 160-cm-deep soil pits. Morphological, agrophysical, and agrochemical soil properties were determined in genetic horizons by standardized and conventional methods [23–25]. Soil samples were taken from five sites in the central part of each genetic horizon and from the plow layer by a soil probe within a radius of 5 m from the pit.

The field experiment was performed in three replications. The total area of the plot was 200 m^2. The crop was assessed by continuous weighting. The data were statistically processed by the variance analysis, using the Statistica 7.0 software package. The reliability of the differences was assessed by the Fisher criterion. The results of analyses of soil samples were represented by the means and their confidence intervals in the form of a double standard deviation [24].

RESULTS AND DISCUSSION

The study of the morphological structure of the soil profile is one of the most informative monitoring methods of soil-forming processes. Prior to the experiment in 2006, the genetic profile of the studied soil included the following horizons: Ap (0–22 cm), A_1A_2 (22–32 cm), A_2B (32–43 cm), B (43–91 cm), BC (91–125 cm), and D (125–160 cm).

During the 12-year-long experiment, the plow horizon of the medium-cultivated soil of the field crop rotation in the absolute control became more lightly colored due to the small input of initial humus-forming substances, and eluviation features in the form of plowed-in pale yellow powder appeared in it. The former transition A_1A_2 horizon was not diagnosed, and the thickness of the A_2B horizon decreased by 7–8 cm. On the background of medium and increased rates of mineral fertilizers, where the mass of post-harvest plant residues exceeded the control variant, the morphological features of accumulative-eluvial soil horizons did not undergo significant changes (Fig. 1).

The most significant positive changes in the structure of the soil profile were related to the application of very high rates of organic fertilizer on the background of lime application (well- and high-cultivated soils). The plow horizon became darker, and its structural status was improved. The lower boundary of the accumulative-eluvial horizons of these soils in both crop rotations became deeper by 13–16 cm, and their density decreased. There were organic matter streaks into the A_2B horizon in high-cultivated soil.

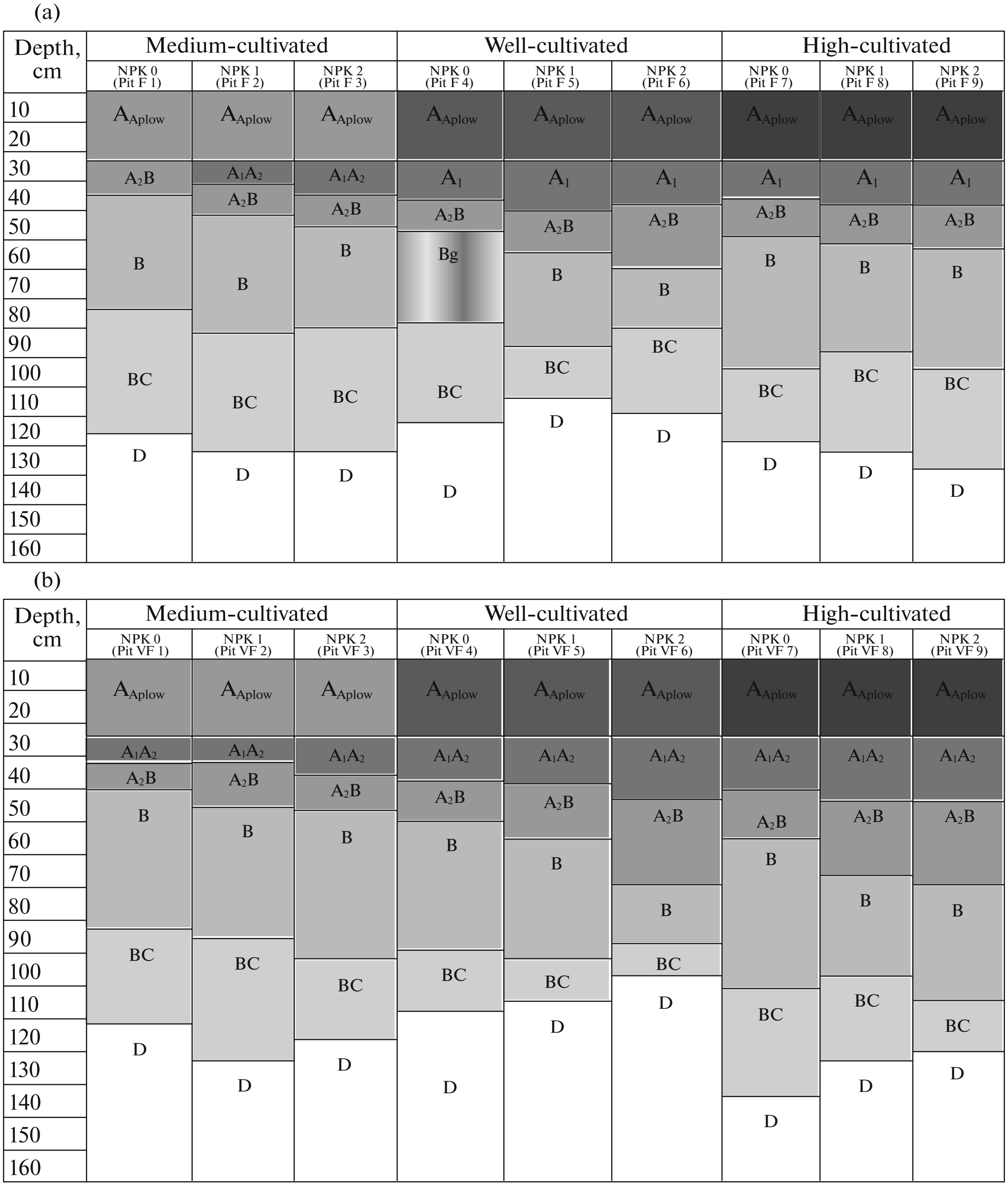

Fig. 1. Structure of the soil profile in crop rotation in 2018: (a) field and (b) vegetable–forage.

The cultivation of perennial and annual herbs in the field crop rotation exerted a positive effect: the A1 humus horizon was formed from the transitional A_1A_2 horizon under less intensive tillage. This was not the case for the vegetable–forage crop rotation with a more intensive tillage and fertilizer system. On the contrary, the soil profile underwent stronger eluviation, on the background of increased rates of mineral fertilizers in particular, as result of which, the total thickness of the A_1A_2 and A_2B horizons increased two times and more.

Mineral fertilizers as a component of measures to restore the fertility of previously degraded soddy-podzolic soil exerted two effects. On the one hand, they favored greater accumulation of initial humus-forming substances in soil and, thus, stimulated the sod process of soil formation. On the other hand, they

Table 1. Agrophysical status of the A_{plow} soil horizon in 2018 (mean for the type of crop rotation, soil cultivation rate, and fertilizer system)

Variant	p_b, g/cm^3	V_{tot}, %	FC, %	Aggregates 0.25–10 mm, %	C_{str}	Water stability, %	C_{ws}
Field*	1.26 ± 0.02	51.5 ± 0.5	25.7 ± 0.5	63.2 ± 1.4	1.7	40.8 ± 0.7	0.69
Vegetable–forage*	1.30 ± 0.01	50.1 ± 0.4	24.2 ± 0.5	60.8 ± 1.1	1.5	32.7 ± 0.7	0.49
Medium**	1.36 ± 0.01	48.7 ± 0.5	21.7 ± 0.5	48.4 ± 0.9	0.9	23.8 ± 0.5	0.31
Good**	1.26 ± 0.02	51.7 ± 0.5	25.5 ± 0.6	61.9 ± 1.2	1.6	39.5 ± 0.8	0.65
High**	1.23 ± 0.02	52.0 ± 0.5	27.6 ± 0.7	72.0 ± 1.0	2.5	47.1 ± 0.8	0.89
Without NPK***	1.29 ± 0.02	50.5 ± 0.5	24.9 ± 0.5	60.3 ± 1.2	1.7	36.7 ± 0.7	0.58
NPK1***	1.27 ± 0.01	51.1 ± 0.3	25.2 ± 0.6	62.8 ± 1.2	1.8	36.8 ± 0.8	0.58
NPK2***	1.29 ± 0.02	50.7 ± 0.4	24.8 ± 0.5	62.9 ± 1.3	1.9	36.8 ± 0.8	0.58

*Crop rotation type, **soil cultivation rate, ***fertilizer system; p_b—bulk density of soil; V_{tot}—total porosity; FC—field capacity; C_{str}—structural coefficient; C_{ws}—water stability coefficient of agronomically valuable aggregates.

became one of the factors of increased weathering of minerals and vertical migration of substances.

The transformation of soil-forming processes under the effect of measures for the reproduction of soil fertility was reflected in different changes in agrophysical and agrochemical soil properties crucial for the agriculture efficiency. Positive changes in these properties were determined to a greater extent by the application of high rates of organic fertilizers in combination with lime application.

By the end of the second crop rotation, the parameters of the plow layers of well- and high-cultivated soils were better as compared to the medium-cultivated soil by 0.10 and 0.13 g/cm^3 (decrease) for the bulk density (p_b), by 3.0 and 3.3% for the total porosity (V_{tot}), and by 3.8 and 5.9% for the field moisture capacity (FC). This enabled an increase in the potential supply of moisture available for plants by 87 and 123 t/ha, respectively (Table 1).

Under the effect of cultivation, the initially unfavorable loose lumpy-powdery structure of soil in the experiment was also improved. In combination with the sowing of herbs, it favored the formation of a good lumpy-granular structure with satisfactory water resistance. The characteristics of well- and high-cultivated soils were better as compared to medium-cultivated soil by 28 and 49% for the portion of agronomically valuable aggregates, by 78 and 178% for the structural coefficient (C_{str}), by 66 and 98% for the water stability of aggregates, and by 110 and 187% for the water stability criterion (C_{ws}), respectively.

Differentiation of agrophysical properties with respect to types of crop rotations was mainly determined by two factors: a positive effect of the sowing of herbs in the field rotation and a negative effect of intensive soil cultivation in the vegetable–forage crop rotation. As a result, the relative difference in the parameters reached 6% for soil compactness, 3% for the total porosity, 6% for the field moisture capacity, 13% for the structural coefficient, 25% for the water stability of aggregates, and 41% for the criterion of their water stability.

The effect of mineral fertilizers on agrophysical soil properties was often insignificant. They stimulated the root growth and the input of crop-root residues and, thus, contributed to better soil structure in the A_{plow} horizon and water stability of aggregates in the subplow layer.

Agrochemical properties of medium-cultivated soil on the background of a negative balance of organic matter and nutrients became significantly poorer in all variants of the experiment. The decrease in pH_{KCl} comprised 0.49 units or 0.041 units per year on average (Table 2). There was a decrease in the content of carbon of organic matter by 0.33% and of mobile compounds of phosphorus and potassium by 115 and 150 mg/kg, respectively. The mean annual losses were 0.028%, 9.6 mg/kg, and 12.5 mg/kg, respectively. Neither moderate nor high rates of mineral fertilizers affected soil acidification, but they slowed down the degradation of the soil phosphate and potassium status.

The change in the properties of well- and high-cultivated soils was determined by the compensation for productive and unproductive losses of nutrients by the application of 75 and 150 t/ha of organic fertilizers in combination (in the corresponding variants of the experiment) with medium or increased rates of mineral fertilizers over the years of the experiment. In the case of smaller removal of NPK and Ca by crops of field rotation, deterioration of agrochemical properties of well-cultivated soil was prevented (exception for potassium provision), but it was impossible for most parameters in the vegetable–forage crop rotation. The decrease in pH_{KCl} (from 6.26–6.53 to 5.87–6.22) and in the content of mobile potassium (from 514–810 to 194–382 mg/kg) was especially significant.

Table 2. Effect of fertility reproduction approaches on agrochemical soil properties

Variant	Year	Agrochemical soil properties (A_{plow}) in crop rotations							
		field				vegetable–forage			
		C_{org}, %	P_2O_5, mg/kg	K_2O, mg/kg	pH_{KCl}	C_{opr}, %	P_2O_5, mg/kg	K_2O, mg/kg	pH_{KCl}
Medium-cultivated soil									
–	2006	1.69 ± 0.02	287 ± 12	223 ± 12	5.60 ± 0.07	1.77 ± 0.02	305 ± 17	233 ± 12	5.62 ± 0.08
NPK 0	2018	1.40 ± 0.02	176 ± 14	48 ± 4	5.18 ± 0.07	1.39 ± 0.02	137 ± 10	57 ± 4	5.16 ± 0.07
NPK 1	2018	1.43 ± 0.03	188 ± 12	61 ± 4	5.11 ± 0.06	1.31 ± 0.03	175 ± 12	107 ± 8	5.10 ± 0.08
NPK 2	2018	1.50 ± 0.03	185 ± 15	68 ± 5	5.14 ± 0.07	1.38 ± 0.03	222 ± 18	126 ± 8	5.02 ± 0.06
Well-cultivated soil									
–	2006	1.93 ± 0.02	330 ± 20	450 ± 23	6.15 ± 0.08	2.37 ± 0.04	368 ± 19	514 ± 31	6.26 ± 0.07
NPK 0	2018	1.95 ± 0.03	352 ± 21	179 ± 16	6.06 ± 0.09	2.01 ± 0.03	413 ± 23	194 ± 16	5.87 ± 0.08
NPK 1	2018	2.04 ± 0.03	371 ± 19	192 ± 13	6.15 ± 0.07	2.17 ± 0.03	409 ± 23	207 ± 14	5.92 ± 0.09
NPK 2	2018	2.06 ± 0.03	353 ± 22	196 ± 11	6.02 ± 0.09	2.15 ± 0.03	402 ± 20	218 ± 16	5.90 ± 0.09
High-cultivated soil									
–	2006	2.15 ± 0.04	420 ± 26	630 ± 31	6.18 ± 0.07	2.36 ± 0.05	447 ± 21	810 ± 52	6.53 ± 0.08
NPK 0	2018	2.46 ± 0.04	405 ± 21	278 ± 20	6.41 ± 0.09	2.35 ± 0.05	446 ± 18	381 ± 25	6.22 ± 0.08
NPK 1	2018	2.57 ± 0.05	387 ± 21	256 ± 25	6.32 ± 0.08	2.41 ± 0.05	410 ± 17	338 ± 20	6.14 ± 0.07
NPK 2	2018	2.60 ± 0.05	428 ± 23	298 ± 24	6.35 ± 0.09	2.47 ± 0.04	427 ± 21	382 ± 25	6.05 ± 0.09

Table 3. Efficiency of means of soil fertility reproduction in the field and vegetable–forage crop rotations

Variant		Field crop rotation			Vegetable–forage crop rotation		
SC* (factor A)	MFS** (factor B)	productivity, thousand grain units/ha	EC PAR, %	economic efficiency, %	productivity, thousand grain units/ha	EC PAR, %	economic efficiency, %
Medium	NPK 0	24.05	2.04	–	24.42	1.74	–
	NPK 1	33.62	2.84	232	31.30	2.21	183
	NPK 2	36.38	3.06	186	31.76	2.26	92
Good	NPK 0	32.20	2.74	–	40.41	2.85	–
	NPK 1	36.67	3.06	174	45.27	3.20	228
	NPK 2	39.67	3.32	142	48.96	3.47	284
High	NPK 0	35.39	3.01	–	45.27	3.19	–
	NPK 1	39.54	3.34	85	48.95	3.46	224
	NPK 2	41.83	3.54	109	50.67	3.57	193
LSD_{05} factor A		2.22			2.97		
factor B		2.84			3.80		

* Soil cultivation rate.
** System of mineral fertilizers.

The productive potentials for the second field and vegetable–forage crop rotation (2012–2017) on medium-cultivated soil were almost the same: 24 000 grain units/ha per rotation (Table 3). It was increased by 34–47 and 65–85%, respectively, by measures of preliminary soil cultivation. The response of crops to soil cultivation was maximal for vegetable crops (white cabbage, in particular); moderate for potatoes, winter cereals, and annual herbs; and minimal for spring cereals and perennial herbs. To a certain extent, this is also the case for the response to mineral fertilizers: their increase at the rates from medium to high was reasonable from the standpoint of agronomic, energy, and economic efficiency on well-cultivated soil in the vegetable–forage crop rotation. In most variants of the experiment, rates of mineral fertilizers higher than the medium level were accompanied by an additional increase in productivity, but this somewhat reduced their economic efficiency.

The efficiency coefficient of photosynthetically active radiation (EC PAR) for crops in the field crop rotation was similar to that in the vegetable–forage crop rotation (the means for the experimental variants were 2.93 and 2.88%, respectively). Soil cultivation to a good and high rate enabled an increase in the EC PAR by 26 and 48% for field crops and by 64 and 83% for the vegetable–forage crop rotation. The use of mineral fertilizers also provided a significant energy effect: it increased the EC PAR by 18– 24% in the field and by 14– 20% in the vegetable–forage crop rotation.

CONCLUSIONS

Thus, the accelerated extended reproduction of fertility of soddy-podzolic soil, which was previously well-cultivated and then underwent degradation, was based on high rates of organic fertilizer and lime application. Subsequent soil use in the field and vegetable–forage crop rotations on the background of medium and increased rates of mineral fertilizers was accompanied by a noticeable transformation of soil-forming processes and soil properties. The main factors of the activation of humus accumulation included an increase in the input of the initial humus-forming substances with manure and greater amount of crop and hay residues under the effect of fertilizers. However, increased rates of mineral fertilizers enhanced eluvial processes, under conditions of vegetable–forage crop rotation in particular. The transformation of the initial soil to the status of well- and high-cultivated over the 12-year-long experiment resulted in an improvement of agrophysical (a decrease in soil density by 0.10 and 0.13 g/cm^3 and an increase in the field moisture capacity by 3.8 and 5.9% and in the portion of agronomically valuable aggregates by 13.5 and 23.6%) and agrochemical (an increase in pH_{KCl} by 0.55 and 0.58, in the carbon content of organic matter by 0.42 and 0.52%, and in mobile compounds of phosphorus and potassium by 53 and 138 and by 254 and 492 mg/kg, respectively) properties of agrosoddy-podzolic soil.

This was finally compensated by a significant increase in crop rotation productivity (by 34–85% due to soil cultivation and by 52–107% due to its combination with complete mineral fertilizer) with high energy and economic efficiency. However, the preservation of the man-made fertility of well- and high-cultivated soils requires significant expenditures for the formation of a deficit-free balance of organic matter and nutrients. Under conditions of vegetable–forage crop rotation, the mean annual application of 6.3 t of organic and 205–310 kg of mineral fertilizers per 1 ha of well-cultivated soil caused stabilization of only mobile phosphates. The application of 12.5 t of organic and 205–310 kg of mineral fertilizers to highly cultivated soil resulted in stabilization of only organic soil matter. The parameters of acid–base and potash status should still remain the objects of special attention for these soils.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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