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SOIL SCIENCE

Biological Activity of Sod-Podzolic Soils in a Long-Term Experiment Involving Various Agrotechnical Methods

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Abstract—The effects from the multiyear use of grain—fallow—plow crop rotation schemes comprising legumes, permanent cultivation of winter rye and barley, and bare fallow regime on the ecological and physiological state of microbial communities in a sod-podzolic heavy loamy soil were examined in the course of a long-term, stationary experiment. Biological activity parameters of soil microbiocoenoses, including the potential intensity of CO_2 emission, microbial biomass gross respiration rate, metabolic coefficient, and nitrogen fixation, were assessed. It is shown that the application of organic fertilizers (manure) in the crop rotation scheme with 28.6% legumes ensures the best humus state of the soil and a significant increase in the total nitrogen content. It is established that the share of microbial biomass (C_{mic}) in the total organic matter of the sod-podzolic heavy loamy soil is 1.50–3.24%. The application of mineral fertilizers results in a slight decrease in the microbial biomass carbon content and increase in the labile organic carbon content. The metabolic activity of microbial communities decreases in all long-term experimental scenarios regardless of the land use techniques. The permanent intensive cultivation of crops, either with or without crop rotation, disturbs the microbiocoenosis stability in soils of the Cis-Ural region.

Keywords: sod-podzolic soil, organic and mineral fertilizers, soil microbiocoenosis, microbial biomass carbon, microbial respiration coefficient, nitrogen fixation

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INTRODUCTION

Optimizing the application of agricultural chemicals is an important aspect of soil fertility's preservation and restoration, improvement of environmental conditions, and formation of high productivity of agricultural crops [1]. The systematic application of organic and mineral fertilizers and cultivation of perennial legumes increases the basic cultivation level of sod-podzolic soils, thus ensuring the sustainable crop capacity amid the reduction of the soil degradation degree down to environmental standards [2]. The results of multiyear studies into the humus transformation and degradation in sod-podzolic soils carried out in the course of long-term, stationary experiments are of utmost interest [3–5]. Such studies take into account the multiyear inflow of various nutrients into the crop rotation system with fertilizers and their outflow with the harvest [6].

The plowing and agricultural use of soils affect the intensity and direction of microbial processes; the microbial community composition drastically changes and mineralization processes are intensified, while the organic matter and total nitrogen contents decrease. Crop rotation schemes with nondeficient nitrogen balance, the capacity for producing nitrogen-containing organic compounds, and increased carbon nutrition of the soil become increasingly important for the restoration of soil fertility [7]. The productivity of arable land is increased and fertility preserved through the activation of biological resources. The nutritional substances return to the soil through the annual inflow of fresh organic matter and activation of the soil microflora [8]. The soil enrichment with symbiotic nitrogen reaches 175–258 kg/ha and greater depending on the perennial legume species, soil fertilization level, and weather conditions [9]. The main soil fertility parameter is its microbiological activity. The humus content is a stable parameter determined by a number of soil properties and its genetic features. The potential carbon dioxide emission and microbial biomass values characterize the physiological activity of the heterotrophic soil microbiota and may be used as its quantitative parameters [10].

The inclusion of soils in the land use system boosts the organic matter mineralization processes, reduces the humus content, and increases the carbon dioxide content of atmospheric air [11]. The carbon dioxide dynamics and production rate make it possible not only to assess the intensity of biological processes but also to estimate the losses of organic matter due to the mineralization processes [12]. Comparative data obtained for agrocoenoses and undisturbed lands make it possible to identify the nature of changes caused by anthropogenic impacts.

The purpose of this study was to examine changes in the biological activity of microbiocoenoses in a sod-podzolic heavy loamy soil maintained for years in the fallow and cultivated condition.

EXPERIMENTAL

The field studies were carried out on the basis of a permanent, stationary study area established in 1977. The soil of the experimental plot is sod-midpodzolic heavy loamy. Its agrochemical parameters at the beginning of the experiment were as follows: humus content = 1.9%; contents of mobile P_2O_5 and exchangeable K_2O were 174 and 158 mg/kg, respectively; pH_{KCl} 4.8; nonexchangeble (total potential) acidity (Hne) = 4.5 mmol/100 g; and S = 21.2 mmol/100 g.

Experimental scenarios: (1) permanent bare fallow, (2) permanent barley cultivation, (3) permanent winter rye cultivation, (4) barley–winter rye–summer wheat–barley–oat crop rotation (0% legumes), (5) manured bare fallow–winter rye–summer wheat + clover–clover (first year of use)–clover (second year of use)–barley–oat crop rotation (28.6% legumes) + manure, (6) green manured fallow (clover (first year of use))–winter rye–summer wheat + clover–clover (first year of use)–clover (second year of use)–barley–oat + clover crop rotation (42.9% legumes), (7) layland.

Mineral fertilizers, $N_{60}P_{30}K_{60}$, were applied before the sowing for cultivation in the form of ammonium nitrate, standard superphosphate, and potassium chloride. Organic fertilizers (litter manure) were applied in the typical crop rotation scheme (28.6% legumes + manure) to the fallow field in the background regime in the amount of 42 t/ha, which translates into 6 t/ha of arable land in the crop rotation. The experiment was carried out with threefold replication; the scenarios were located in sequence using the split parcel method. The fractional and group composition of humus was determined using the Ponomareva–Plotnikova method [13]; nitrogen fractions were measured using the method suggested by Koroleva and Shkonde [14].

The basal respiration (BR) and substrate-induced respiration (SIR) values were determined using the methodology suggested by Anan'eva et al. [15]. The soil respiration parameters were expressed in μg CO_2/g of soil h. The microbial biomass carbon content (C_{mic}) was calculated as $V_{SIR μL\ CO_2/g\ of\ soil/h}$ 40.04 + 0.37; the relative microbial respiration coefficient (*QR*) was calculated as the ratio between the absolute BR value and SIR (V_{BD}/V_{SIR}). The acetylene method was used for nitrogen fixation activity measurement. The potential nitrogen fixation activity was expressed in μg ethylene/kg of soil h [16]. The measurements were carried out with threefold replication. The statistical processing of the data was performed using Excel 2007 software.

RESULTS AND DISCUSSION

In a seven-field rotation system, which is typical for the Cis-Ural region, with two clover fields and manure concentration of 6 t/ha, the humus content increased by 33% in comparison with the initial level due to the cumulative interaction of bioresources of the cultivated legume and grain crops. The perpetual soil maintenance as a fallow land for 40 years has resulted in the soil depletion of humus and nitrogen; the humus loss amounted to 30% of its initial content at the beginning of the experiment. The organic matter humification degree (Cha : Cfa) varied from 0.55 in the perpetual fallow to 0.96 in the layland. The analysis of data on the humus content in soil samples from various scenarios (Table 1) shows that it reliably decreases in the following row: crop rotation (28.6% legumes) + manure > layland > crop rotation (0% legumes) = crop rotation (42.9% legumes) > barley > winter rye > bare fallow.

Nonhydrolyzable and hardly hydrolyzable nitrogen forms respectively constitute 43–57 and 28–40% of the nitrogen pool of the sod-podzolic soil used in the long-term, stationary experiment. The long-term application of the complete mineral fertilizer (NPK) increases the content of hydrolyzable nitrogen forms and absolute percentage of the easily hydrolyzable fraction. The crop rotation scheme with two clover fields and application of manure and mineral fertilizers results in the maximum accumulation of nitrogen fractions available for plants. The perpetual soil maintenance as a fallow land and use of grain crop rotation schemes exhaust the soil. Various land use techniques do not change the ratio of nitrogen fractions typical for sod-podzolic soils of the Cis-Ural region [17].

The respiratory activity, or basal respiration (BR), of the sod-podzolic heavy loamy soil (in the 0–20-cm layer) decreases in the following order depending on the land use type: layland > crop rotation (28.6% legumes) + manure > crop rotation (42.9% legumes) > crop rotation (0% legumes) > barley > winter rye > bare fallow (Table 2). The CO_2 emission from the layland was 2.85 times higher in comparison with the perpetual bare fallow. Additional application of $N_{60}P_{30}K_{60}$ reduces the carbon dioxide level in crop rotation schemes with various contents of legumes by 4–5%

Table 1. Agrochemical parameters of the sod-podzolic soil under various land uses

Factor A—land use type		pH_{KCl}	Humus, %	Cha : Cfa	Total nitrogen, %	N_{hh}, mg/kg	N_{eh}, mg/kg	N_{min}, mg/kg
No mineral fertilizers								
Crop rotation (28.6% legumes) + manure		5.46	2.53	0.76	1729	564	217	8.9
Crop rotation (0% legumes)		5.19	1.89	0.72	1295	423	205	6.7
Crop rotation (42.9% legumes)		4.90	1.90	0.78	1428	507	247	8.7
Barley		5.14	1.88	0.72	1442	423	217	7.9
Winter rye		5.10	1.81	0.70	1441	448	227	7.1
Layland		4.84	2.35	0.96	1554	553	300	5.2
Bare fallow		4.99	1.34	0.55	980	396	175	7.0
NPK								
Crop rotation (28.6% legumes) + manure		5.33	2.51	0.78	2058	591	284	10.8
Crop rotation (0% legumes)		5.05	1.93	0.72	1281	419	222	7.0
Crop rotation (42.9% legumes)		5.04	1.92	0.79	1449	560	258	9.2
Barley		5.01	1.77	0.76	1624	557	279	7.3
Winter rye		5.12	1.83	0.76	1449	568	230	6.8
Main effects	of factor A	0.06	0.12		296	Ff < Ft	Ff < Ft	Ff < Ft
	of factor B and AB interaction	0.05	Ff < Ft		Ff < Ft	47.93	Ff < Ft	Ff < Ft
Specific differences	of the first order	0.08	0.18		419	160.18	67.36	1.6
	of the second order	0.14	0.13		149	107.18	43.78	2.7

and increases the BD in scenarios with perpetual cultivation of winter rye and barley by 32 and 2%, respectively. Aside from the layland, the highest SIR values were registered in the crop rotation scheme with 28.6% of legumes + manure without NPK (7.89 μg CO_2–C/g h) and with NPK application (8.30 μg CO_2–C/g h). The nitrogen-fixing activity of the soil microflora in the crop rotation scheme with 28.6% legumes + manure was 20% higher than in the crop rotation scheme with 42.9% legumes (Table 2). The application of $N_{60}P_{30}K_{60}$ suppressed the functional activity of nitrogen-fixing bacteria by 22% in the in the crop rotation scheme with 28.6% legumes + manure + NPK and by 90% in the crop rotation scheme with 42.9% legumes + NPK.

The microbial biomass carbon content (C_{mic}) is a sensitive indicator of the soil organic matter quality and dynamics of its changes. C_{mic} values in the soil without NPK varied from 157.78 μg/g in the perpetual winter rye cultivation scenario to 439.98 μg/g in the layland (Table 3). The share of C_{mic} in the organic matter of the sod-podzolic heavy loamy soil was 1.50–3.24%. In all studied land use scenarios, the C_{mic}/C_{org} ratio was lower than 2.3%, which indicates losses of organic carbon. High values of the metabolic coefficient (q_{CO_2}) are caused by the high die-off rate of the microbial biomass in the soil. This, in turn, is caused by the functional degradation of the soil's microbial community. With the use of fertilizers, the highest (q_{CO_2}) values were registered for the perpetual winter rye cultivation scenario and crop rotation scheme with 42.9% legumes + NPK (Table 3).

The quantitative assessment of disturbances in the microbial community on the basis of the microbial respiration coefficient (*QR*) has also shown degradation of the microbial community's stability in all scenarios. The *QR* values varied from 0.325 to 0.494, which indicates an average level of the microbiocoenosis stability (Table 2).

CONCLUSIONS

The intensive multiyear cultivation of crops, either with or without crop rotation, adversely affects the microbial community's stability in sod-podzolic heavy loamy soils. The activity of soil microbiocoenoses largely depends on the total organic carbon pool. The transfer of arable soil into layland contributes to the organic matter accumulation in the upper layer; this boosts the soil respiratory activity and increases its microbial carbon pool. The metabolic activity of microbial communities decreases in all long-term experimental scenarios regardless of the land use techniques. Additional application of mineral fertilizers, $N_{60}P_{30}K_{60}$, to crop rotation schemes with

Table 2. Biological parameters reflecting the state of the microbial community in the arable layer of the sod-podzolic soil

Scenario	C_{org}, %	BR, μg CO_2–C/g h	SIR, μg CO_2–C/g h	*QR*	Nitrogen fixation, μg C_2H_4/kg h
No mineral fertilizers					
Winter rye	1.05	1.94 ± 0.23	3.93 ± 0.41	0.494	33.08 ± 2.25
Barley	1.09	2.07 ± 0.19	5.50 ± 0.28	0.376	15.54 ± 1.74
Crop rotation (0% legumes)	1.10	2.12 ± 0.17	4.71 ± 0.48	0.450	18.70 ± 4.35
Crop rotation (28.6% legumes) + manure	1.47	2.84 ± 0.26	7.89 ± 0.38	0.360	44.10 ± 7.20
Crop rotation (42.9% legumes)	1.10	2.66 ± 0.32	6.41 ± 0.78	0.415	35.64 ± 5.56
Bare fallow	0.78	1.66 ± 0.30	4.87 ± 0.51	0.341	11.53 ± 2.38
Layland	1.36	4.73 ± 0.89	10.98 ± 0.90	0.431	16.04 ± 4.59
NPK					
Winter rye	1.06	2.11 ± 0.44	5.31 ± 0.39	0.397	7.52 ± 1.50
Barley	1.03	2.55 ± 0.21	5.66 ± 0.62	0.451	44.15 ± 6.52
Crop rotation (0% legumes)	1.11	2.12 ± 0.29	5.20 ± 0.56	0.408	16.04 ± 2.30
Crop rotation (28.6% legumes) + manure	1.46	2.70 ± 0.39	8.30 ± 0.36	0.325	34.33 ± 5.67
Crop rotation (42.9% legumes)	1.11	2.51 ± 0.40	5.12 ± 0.39	0.490	3.51 ± 2.30

Table 3. Specific microbial respiration (q_{CO_2}) and share of microbial carbon (C_{mic}) in the total organic carbon content (C_{org}) and labile organic carbon content (C_{lab}) (extracted by sodium pyrophosphate solution) in the sod-podzolic soil under various land uses

Scenario	C_{mic}, μg/g	q_{CO_2}, μg CO_2–C/mg C_{mic}/h	C_{mic}/C_{org}, %	C_{mic}/C_{lab}, $Na_2P_2O_7$, %
No mineral fertilizers				
Winter rye	157.78	2.30	1.50	8.30
Barley	220.43	1.76	2.02	10.50
Crop rotation (0% legumes)	188.72	2.11	1.72	8.58
Crop rotation (28.6% legumes) + manure	316.14	1.68	2.15	12.65
Crop rotation (42.9% legumes)	257.10	1.93	2.34	11.69
Bare fallow	195.53	1.59	2.51	11.50
Layland	439.98	2.01	3.24	14.67
NPK				
Winter rye	212.79	2.25	2.00	10.64
Barley	226.00	1.74	2.20	9.46
Crop rotation (0% legumes)	209.34	1.90	1.89	7.48
Crop rotation (28.6% legumes) + manure	332.59	1.52	2.28	13.86
Crop rotation (42.9% legumes)	205.15	2.30	1.85	9.77

legumes suppresses the nitrogen-fixing activity of microbiocoenoses.

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COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflict of interest. This article does not contain any studies involving animals or human participants performed by any of the authors.

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