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AGRICULTURAL CHEMISTRY AND SOIL FERTILITY

Cycles, Nitrogen Budget, and Sustainability of Agroecosystems after Applying Organic Fertilizers (Labeled with ^{15}N)

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Abstract—The nitrogen of organic fertilizers contributes to stabilization of nitrogen cycles and sustainable development of agroecosystems. The application of green manure biomass as organic fertilizer enhances the immobilization of their nitrogen in soil, reduces the nitrogen consumption by plants and its gaseous losses as compared with mineral fertilizers. A combined use of the green manure biomass and mineral nitrogen fertilizers decreases the nitrogen immobilization in soil as well as increases its consumption by plants and its gaseous losses. The application of manure reduces the nitrogen gaseous loss from green manure biomass. The use of the oat and timothy biomasses as a fertilizer decreases the consumption of their nitrogen and soil nitrogen by plants by 18–36 and 6–36%, respectively, while the nitrogen immobilization in soil increases and its gaseous losses decrease by 17% as compared with the application of mineral fertilizers alone.

Keywords: ^{15}N, ^{15}N-labeled grass biomass, nitrogen budget, mineralization, immobilization, soddy-podzolic soil, Stagnic Retisol (Loamic Humic), typical chernozem, Haplic Chernozem (Loamic, Pachic)

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INTRODUCTION

Under conditions of limited resources, the use of organic fertilizers and design of ecologically safe technologies of their application are required to provide sustainable development of agroecosystems, maintenance of soil fertility, optimization of production process, and stabilization of production quality [9, 19]. The sustainability of an agroecosystem is understood as its capacity to retain and maintain its characteristics and structure in space and time without any qualitative change in its function.

In 2019, the level of applied organic fertilizers in Russia was only 1.6 t/ha of cropland. That is why, the importance of perennial legume–grass cultures and green manure crops, which are important sources of organic matter and nitrogen for arable lands, is ever increasing. These cultures are two- or three-component mixtures with timothy, bromegrass, fescue, or bluegrass as a cereal component and clover, alfalfa, sainfoin, or melilot as a legume component. The legume–grass mixtures are used as green manure in crop rotation as well as the forage for cattle. The relations between the legumes and grasses in mixed crops provide for highly productive ecologically and economically efficient agrophytocenoses. Legume biomass provides the input of a large amount of easily decomposable organic substances introducing the biological nitrogen into agrocenoses, thereby enhancing stabilization of the humus state and improving soil physicochemical properties, biogenicity, and phytosanitary state [6, 7, 14, 16]. On entering the soil, green manure biomass becomes the energy basis for the life activities of the microorganisms fixing molecular nitrogen and transforming nitrogen compounds. However, the issues associated with the efficiency of green manure nitrogen utilization by crops and the patterns of nitrogen transformation in soil are still poorly studied [5, 14, 24].

The goal of this work was to assess the turnover parameters of nitrogen of various crops used as green manure at different levels of mineral nutrition.

OBJECTS AND METHODS

The studies were performed in different soil and climatic regions of this country, namely, Nonchernozem region (medium sandy loamy soddy-podzolic soil, or Albic Retisol (Loamic, Aric); Smolensk, Russia) and Central Chernozem region (heavy sandy loamy typical chernozem, or Haplic Chernozem (Loamic, Pachic); Belgorod, Russia). The effect of different grass species was assessed. The ^{15}N-labeled biomass was obtained by growing the grasses in individual plots under field conditions with application of

Table 1. Characterization of dry biomass of different ^{15}N-labeled grasses

Characteristic	Experiment 1	Experiment 2			Experiment 3	
	white mustard	timothy	lupine	clover	oat	timothy
C/N	21	27	23	19	34	27
N_{tot}, %	3.3	2.0	2.80	2.50	1.58	1.84
^{15}N, at %	15.3	13.1	15.0	14.5	16.4	18.1
N dose applied with biomass, g/m^2	6.01	5.01	5.04	5.02	5.03	5.05

highly enriched (over 90 at %) mineral nitrogen fertilizers.

Experiment 1. The flows and budget of the nitrogen of white mustard during the growth of the winter wheat cultivar Gubernator Dona were studied in a micro field experiment (bottomless containers with a size of 23 × 45 × 30 cm) on Haplic Chernozem in the forest-steppe zone of the Belgorod oblast. Fertilizers at a dose of $N_6P_6K_6$ g/m^2 were applied in the fall prior to sowing. Of the nitrogen fertilizers, we used ^{15}N-labeled urea (13.3 at %) and of the phosphorus and potassium fertilizers, double superphosphate and potassium chloride. The experiment comprised the following variants: P_6K_6 (background), background + ^{15}N-labeled white mustard in an amount equivalent to N_6, background + $^{15}N_u$ (urea nitrogen; Table 1), and background + 2/3 dose of ^{15}N white mustard + 1/3 dose of N_u.

The ^{15}N-labeled white mustard biomass was produced 1 year before the main experiment. For this purpose, the white mustard was grown in an individual plot fertilized with highly enriched ^{15}N-labeled ammonium sulfate (92.2 at % of ^{15}N). The plants were harvested during mass flowering, dried in the shade to the air-dry state, minced into 0.3–0.5-cm fragments, and applied in the fall at a dose of 6.01 g N/m^2 as a nitrogen fertilizer (3.3% N, 15.3 at % ^{15}N) on the background of P_6K_6. All doses of the used grasses are given with respect to the nitrogen content, which makes it possible to compare the availability and efficiency of their application. The hydrothermal index (HTI) over the growing season of the winter wheat was 0.9 versus the long-term average of 1.2. The air temperature over the growing season matched the average long-term average value and the precipitation amount was 1.3-fold lower as compared with the average long-term value.

Experiment 2. The nitrogen budget in ^{15}N-labeled biomasses of different grasses during the growth of the oat cultivar Skakun was studied in a micro field experiment on medium loamy soil in the Smolensk oblast. The area of experimental plots was 0.5 m^2 (0.5 × 1.0 m). Initially, the narrow-leaved lupine, red clover, and timothy were sown in the plots fertilized with ammonium sulfate enriched with ^{15}N (>95 at %). The final dry biomass contained 13.1–15.0 at % of ^{15}N and 2.0–2.8% of total nitrogen; the biomass was minced into fragments of 0.3–0.5 cm and applied to the plots at a dose of 5.01–5.04 g/m^2 on the background of phosphorus and potassium fertilizers P_5K_5 (double superphosphate and potassium chloride, respectively). The HTI over the oat growing season amounted to 1.4 versus the long-term average of 1.7. The air temperature over the growing season was 1.1-fold higher and the amount of precipitation, 1.2-fold lower as compared with the long-term average value.

Experiment 3. The nitrogen flows and budget of the ^{15}N-labeled oat and timothy biomasses during the growth of the barley cultivar Nosovskii 9 were studied in a micro field experiment (bottomless containers with a size of 50 × 50 × 40 cm) in the same soil as in experiment 2. For this experiment, the oat and timothy were preliminary grown and fertilized with ammonium sulfate highly enriched with ^{15}N (>95 at %). The resulting oat and timothy biomass was minced and applied to soil in the fall at a dose of 5.03–5.05 g N/m^2 on the background of phosphorus and potassium fertilizers P_5K_5 (double superphosphate and potassium chloride, respectively). Semirotted manure (32% C and 1.16% N_{tot}) was used at a dose of 10 t/ha. Nitrogen fertilizers as ammonium sulfate (26.85 at %) were applied at a dose of 5 g N/m^2 on the background of P_5K_5 prior to sowing the barley at a depth of 10 cm. The meteorological conditions were favorable for raising barley; the HTI over the growing season was 1.7, matching the long-term average.

Table 2 shows the agrochemical characteristics of the soil in experimental plots. Mineral (residual) nitrogen in the soil was determined as the total ammonium nitrogen since the nitrates were preliminary reduced with the help of Devardo's alloy [10]. The total nitrogen in plant and soil samples was analyzed using the classical Kjeldahl–Jodlbauer method at the Laboratory of Mineral and Biological Nitrogen. The nitrogen isotope composition in soil and plant samples was determined in a Delta V mass spectrometer at the Laboratory of Interdisciplinary Studies with the Pryanishnikov All-Russia Institute of Agricultural Chemistry.

The amount of nitrogen in labeled fertilizers either present in plants or retained in soil after plant growth was determined as

$$N_{fert} = \underline{N_{tot}(c-b)/(a-b)},$$

Table 2. Agrochemical characterization of soil of the experimental plots

Characteristic		Experiment 1	Experiments 2 and 3
Organic matter content according to Tyurin, %		5.0	2.1
pH_{salt}		6.5	5.7
Hydrolytic acidity, cmol(equiv)/kg		1.32	1.2
Total nitrogen content according to Kjeldahl–Jodlbauer,%		0.23	0.09
Content of exchangeable bases, mmol/100 g soil	Ca^2	26.7	5.5
	Mg^{2+}	2.81	2.0
Content of exchangeable compounds, mg/kg	P_2O_5	118*	137**
	K_2O	140*	138**

* According to Chirikov.
** According to Kirsanov.

where N_{fert} is the amount of labeled fertilizer nitrogen in plants (soil); N_{tot} is the amount of total nitrogen in plant (soil); a, amount of ^{15}N in labeled fertilizer nitrogen, at %; b, amount of ^{15}N in unlabeled plants (soil) nitrogen, at %; and c, amount of ^{15}N in labeled plants (soil), at %.

The data on the consumption of fertilizer nitrogen and the nitrogen immobilization in the soil were used to assess the nitrogen budget. The nitrogen of gaseous compounds was determined as the difference between the nitrogen share and the total amount of nitrogen taken up by plants and immobilized in the soil.

The flows of fertilizer nitrogen and soil nitrogen were calculated as follows [11]:

Immobilized nitrogen, $N_c = N_a \times {}^{15}N_c/{}^{15}N_a$;

Nitrogen gaseous losses, $N_d = N_a \times {}^{15}N_d/{}^{15}N_a$;

Mineralized nitrogen, $M = N_a + N_b + N_c + N_d$;

Net mineralized nitrogen, $N\text{-}M = M - (N_c + N_b)$; and

Re-immobilized nitrogen, $RI = M - N\text{-}M$,

where N_a is the removal of total nitrogen with harvest; $^{15}N_a$ is the consumption of fertilizer nitrogen; $^{15}N_c$ is immobilized fertilizer nitrogen; N_b is residual mineral nitrogen; and $^{15}N_d$ is fertilizer nitrogen gaseous losses.

The degree of stability was assessed using the criteria for an integral estimate (classification) of the functioning regimes of ecosystems and the level of impacts on them (Table 3).

The data on the grain yields of winter wheat, oat, and barley were processed using ANOVA (STAT VNIIA); statistical significance was assessed using Fisher's test.

RESULTS AND DISCUSSION

A positive effect of the white mustard on agrophysical and agrochemical properties of soil is described in literature in sufficient detail. However, the involvement of mustard nitrogen in nitrogen cycling and production of crops is insufficiently studied [3, 8, 13, 18].

The winter wheat grown on typical chernozem consumed lower amount of mustard nitrogen as compared with urea nitrogen (Table 4). Application of urea together with mustard increased the amount of nitrogen from its biomass used by plants. In this process, a larger amount of mustard nitrogen was immobilized in soil as compared with the urea nitrogen and a smaller amount of mustard nitrogen was lost.

In soddy-podzolic soil, oat better utilized the nitrogen of clover biomass; a smaller amount of clover nitrogen was immobilized in soil and lost as a gas. The timothy nitrogen was to a lesser degree consumed by oat plants and its considerably larger amount was immobilized. In addition, oat more efficiently utilized not only the nitrogen of clover biomass, but also soil nitrogen. According to the published data, oat consumed 2.6 units of soil nitrogen per 1 unit of clover nitrogen as compared with the timothy nitrogen (1.4 units of soil nitrogen per 1 unit of timothy nitrogen) [19, 22]. The nitrogen of clover biomass is more actively incorporated into microbial biomass and is more readily involved into the synthesis of humic acids of soil organic matter [20, 32, 33].

Table 3. Criteria of functioning regimes of agroecosystems [11]

Functioning regime	Level of impact	Criterion	
		RI/M, %	N-M/RI, %
Homeostasis	Norm	50 ± 5	0.8–1.2
Stress	Permissible	45–30	1.2–2.5
Resistance	Maximum permissible	30–20	2.5–4.2
Adaptation exhaustion	Critical	20–10	4.2–9.0
Repression	Impermissible	<10	>9.0

Table 4. Flows and budget of the nitrogen of crop biomass after application of ^{15}N-labeled organic fertilizers

Variant	Utilization by plants		Immobilized in 0–40-cm soil layer		Gaseous losses	
	g/m^2	% of dose	g/m^2	% of dose	g/m^2	% of dose
Winter wheat						
Background + ^{15}N-mustard	1.89	32	3.45	58	0.66	10
Background + 2/3 ^{15}N-mustard + 1/3 N_u	2.37	40	2.73	45	0.90	15
Background + $^{15}N_u$	2.64	44	1.58	33	1.38	23
Oat						
Background + ^{15}N-clover	1.85	37	2.76	55	0.41	8
Background + ^{15}N-lupine	1.40	28	3.02	60	0.62	12
Background + ^{15}N-timothy	0.84	17	3.46	69	0.71	14
Barley						
Background + ^{15}N-oat	1.30	26	2.74	55	0.96	19
Background + ^{15}N-oat + manure$_{10}$	1.60	32	2.80	58	0.60	12
Background + ^{15}N-timothy	1.50	30	2.84	57	0.66	13
Background + ^{15}N-timothy + manure$_{10}$	1.68	34	2.92	58	0.40	8
Background + $^{15}N_5$	2.04	41	1.66	33	1.30	26

* Manure$_{10}$, manure at a dose of 10 t/ha.

Barley plants consumed considerably smaller (1.6-fold) amount of oat and timothy biomass, while the immobilization of their nitrogen increased (1.3–1.6-fold) as compared with mineral fertilizers. The immobilization of the nitrogen of oat and timothy biomasses increased with the application of manure. The immobilization of the nitrogen of ^{15}N-labeled green oat biomass decreases when applied together with mineral fertilizers [15]. The immobilization of clover and mustard nitrogen also decreases when applied in combination with nitrogen fertilizers [12, 19].

The input of the fresh organic matter with a wide carbon to nitrogen ratio (manure) to soil considerably increases the activity of autochthonous and zymogenic microflora, and a more active and diverse microbial community is formed [21, 25, 27, 29].

The content of nitrogen is of primary importance in the decomposition of plant material [23, 26, 31]. Initially, the biomass of legumes with a narrower C/N ratio was mineralized more rapidly as compared with the biomass of cereal grasses [28, 34]. The nitrogen immobilization in soil increases with the narrowing of the carbon to nitrogen ratio (timothy and manure). The biomass decomposes faster in the case of a narrower C/N ratio, thereby minimizing the soil enrichment with humus [30]. The content of organic carbon in the soil fertilized with manure increases by 6.4–9.8% and with straw, by 3.7–5.2%, whereas the application of green manure can even lead to a decrease in humus content. The more intensive the nitrogen immobilization in soil, the smaller are the gaseous losses [21, 27].

The gaseous losses of oat and timothy nitrogen are considerably smaller (1.4- and 2-fold, respectively) as compared with those in case of nitrogen fertilizers. Manure additionally reduced the losses of oat and timothy nitrogen (1.6-fold). According to the published data, the losses of the nitrogen of plant residues from soil decrease 1.3–1.5-fold as compared with nitrogen fertilizers [15]. Green manure and cereal biomass reduce 1.3–2.4-fold the gas losses of mineral fertilizer nitrogen and 1.6-fold, of soil.

The changes in the intensity of nitrogen cycle in soil, the role of the ratio in an integral estimate of the degree of stability, and the yield of cereal crops were assessed according to Pomazkina [11]. The soil nitrogen mineralized over the growing season (M) may be regarded as the "input" of matter to the ecosystem. Net mineral nitrogen (N-M), i.e., the amount of mineral nitrogen utilized by plants and lost as gaseous compounds, is the "output", while the re-immobilized nitrogen (RI), maintaining the sustainability of the system, is the "payback at the output" [17]. The data on mineral of soil nitrogen were obtained using these equations (Tables 1 and 5).

Depending on the applied fertilizers (oat and timothy biomasses), the intensity of the processes of nitrogen cycle in soil (mineralization ↔ immobilization/re-immobilization) changed (Table 5). Plant biomass and manure activated the immobilization/re-

Table 5. Soil and fertilizer nitrogen flows after applying ^{15}N-labeled oat and timothy biomass to growing barley, g/m^2

Variant	Removal of soil nitrogen by plants	Residual mineral nitrogen	Immobilized/re-immobilized soil nitrogen	Gaseous losses of soil nitrogen	Mineralized nitrogen (M)	Net mineralized nitrogen (N-M)	Re-immobilized nitrogen (RI)	Fertilizer nitrogen utilized by plants	Immobilized fertilizer nitrogen	Gaseous losses of fertilizer nitrogen
Background + $^5N_5$	10.3	2.55	15.11	11.83	39.52	24.41	12.56	2.04	1.66	1.30
Background + ^{15}N-oat	6.38	1.94	24.93	8.74	41.89	16.93	23.09	1.30	2.74	0.96
Background + ^{15}N-oat + manure$_{10}$	7.88*	1.51*	25.48	5.46	40.33	14.85	23.97	1.60	2.80	0.60
Background + ^{15}N-timothy	7.36	1.71	25.84	6.01	40.92	15.08	24.13	1.50	2.84	0.66
Background + ^{15}N-timothy + manure$_{10}$	9.25*	1.67*	26.57	3.64	41.13	14.56	24.90	1.88	2.92	0.40

* N soil + N manure.

immobilization processes, thereby increasing the concurrent mineralization of soil organic matter, while its net mineralization decreased as compared with the effect of nitrogen fertilizers. In this process, the biomass caused a decrease in the share of net mineralization of soil nitrogen (36–40% of mineralized nitrogen) as compared with nitrogen fertilizers (62%). The increase in soil nitrogen mineralization and the decrease in its net mineralization are associated with the decrease in the nitrifying bacteria population caused by straw [2]. A large share of the net mineralization of soil nitrogen caused its more intensive gaseous losses as compared with the oat and timothy biomasses.

The organic matter of oat and timothy biomasses is involved in the formation of soil organic matter by generating mobile humification products [20, 32]. An increase in immobilization of biomass and soil nitrogen after applying semirotted manure is most likely associated with incorporation of their nitrogen into the biomass of the microorganisms entering soil with manure [32].

Presumably, a combined application of liquid manure and cereal straw will give a more pronounced effect since manure contains a larger amount of mobile nitrogen [2, 19].

The ratio of net mineralized nitrogen (N-M) to re-immobilized nitrogen (RI), which quantitatively characterizes the dependence between nitrogen flows directed to heterotrophic and autotrophic cycles, is an integral characteristic of the agroecosystem sustainability [4, 11, 24]. Pomazkina [11] gives examples of ecosystem sustainability with respect to nitrogen cycle according to the criteria of agroecosystem functioning regime. The winter wheat agrophytocenosis on typical chernozem after applying the white mustard is in the stress zone at a permissible level of impact (Table 6). However, the agrophytocenosis was at a lower level of ecological sustainability after a joint application of the mustard biomass and urea as compared with the mustard biomass alone. Mineral nitrogen fertilizers somewhat decreased the sustainability of the system since they caused an increase in nitrogen mineralization and nitrogen gaseous losses from the mustard biomass and soil and a decrease in their immobilization/re-immobilization [19].

In soddy-podzolic soil, the agrophytocenosis of green manure crops was in a more stable form (in the zone of homeostasis at a normal level of the impact) after applying the timothy biomass compared with clover and lupine biomasses (at a boundary state between the homeostasis and stress zones). This is determined by an increase in of green manure mineralization and of soil nitrogen. The ecological sustainability of the agrophytocenosis emerged to be lower after applying mineral nitrogen fertilizers alone as compared with the application of grass biomass [19].

The application of oat and timothy biomasses as green manure to soddy-podzolic soil as well as their combined application with manure elevated the sustainability of barley agrophytocenosis to the regime of homeostasis at a permissible level of impact. This results from a considerable immobilization/re-immobilization of nitrogen of oat and timothy biomasses, which are the crops with a wider C/N ratio [18, 20]. The biomass of cereal and legume crops has an integrated effect on the function of agrophytocenosis by influencing the mineralization and immobilization of soil nitrogen, ameliorating soil phosphorus and potassium regimes, improving soil agrophysical properties, and increasing the efficiency of photosynthesis via additional CO_2 emission during decomposition of the biomass, which results in a higher yield of the cultivated crops [29].

Table 6. The effect of applied mineral and organic fertilizers on the characteristics of integral estimate of agrophytocenosis functioning

Variant	Characteristics of stability	
	RI/M, %	(N-M)/RI
Winter wheat		
Background + ^{15}N-mustard	44	1.1
Background + 2/3 ^{15}N-mustard + 1/3 N_u	37	1.5
Background + $^{15}N_u$	33	1.9
Oat		
Background + ^{15}N-clover	44	1.1
Background + ^{15}N-lupine	45	0.9
Background + ^{15}N-timothy	62	0.5
Barley		
Background + ^{15}N-oat	55	1.4
Background + ^{15}N-oat + manure$_{10}$	59	1.6
Background + ^{15}N-timothy	59	1.5
Background + ^{15}N-timothy + manure$_{10}$	60	1.7
Background + $^{15}N_5$	32	1.9

Table 7. Yields of crops depending on the type of organic fertilizers

Variant	Grain yield, g/m^2	Increase in yield	
		g/m^2	%
Winter wheat			
Background (P_6K_6)	664	–	–
Background + ^{15}N-mustard	829	165	24.8
Background + 2/3 ^{15}N-mustard + 1/3 N_u	875	211	31.8
Oat			
Background (P_5K_5)	176	–	–
Background + ^{15}N-clover	384	208	118.2
Background + ^{15}N-lupine	296	120	68.2
Background + ^{15}N-timothy	266	90	51.1
Barley			
Background (P_5K_5)	185	–	–
Background + ^{15}N-oat	304	119	64.3
Background + ^{15}N-oat + manure$_{10}$	349	164	88.6
Background + ^{15}N-timothy	335	150	81.1
Background + ^{15}N-timothy + manure$_{10}$	376	191	103.2
Background + $^{15}N_5$	432	247	133.5

The productivity of winter wheat is an integral characteristic of an increase in the degree of soil nitrogen mineralization. The maximum yield of winter wheat grain was achieved in the variant with typical chernozem and combined application of urea and mustard biomass because this increased green manure mineralization and soil nitrogen content (Table 7). The minimum yield of winter wheat was observed in the variant with mustard biomass alone because of a resulting decrease in the consumption of green manure and soil nitrogen by plants [1, 19].

The highest yield of oat grain was achieved in the variant with soddy-podzolic soil and clover biomass, which results from a more active utilization of nitrogen of this green manure type and soil. The oat yield decreased 1.4-fold when the timothy biomass was used as a green manure and 1.3-fold with the lupine biomass [33]. This results from a more active use of the clover nitrogen by soil microorganisms and the fact that this nitrogen to a larger degree is incorporated into humic acids (as compared with the nitrogen of lupine and timothy), thereby providing better nutrition of plants and an increase in grain yield [20, 32].

The barley grown on soddy-podzolic soil on the P_5K_5 background variant gave the same grain yield as the oat. The highest barley yield was formed after the application of ammonium sulfate because of the most efficient utilization of fertilizer and soil nitrogen by oat plants. In the variant with oat and timothy biomasses (separately or combined with manure), the productivity of barley decreased by 13–30% as compared with nitrogen fertilizers.

CONCLUSIONS

The nitrogen of organic fertilizers (green manure biomass) contributes to the stabilization of nitrogen cycles and sustainability of agroecosystems. The application of this biomass increases the nitrogen immobilization in the soil and reduces the utilization of nitrogen by plants and its gaseous losses as compared with mineral nitrogen fertilizers. A joint application of green manure biomass and nitrogen fertilizers decreases nitrogen immobilization in soil with a concurrent increase in its utilization by plants and its gaseous losses. Manure reduces the gaseous losses of the nitrogen of green manure biomass. When oat and timothy biomasses are applied, the consumption of their nitrogen and soil nitrogen by plants decreases by 18–36 and 6–36%, respectively, while the immobilization of nitrogen in soil increases and its gaseous losses are reduced. Green manure crops increase the sustainability of an agroecosystem to the regimes of homeostasis or stress. The agroecosystem with applied timothy biomass displays the highest stability. Nitrogen fertilizers decrease the sustainability of agroecosystem.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. A. S. Awilow, O. A. Sokolov, A. A. Zavalin, and N. Ya. Shmyreva, "Nitrogen transformation by white mustard biomass in soil," Dostizh. Nauki Tekh. APK **30** (2), 29–31 (2016).
2. I. V. Vernichenko, *Assimilation of Ammonium and Nitrate Nitrogen by Plants and Endogenous Synthesis of Nitrates (Studies with ^{15}N)* (Russian State Agrarian University–Moscow Timiryazev Agricultural Academy, Moscow, 2017) [in Russian].
3. A. V. Dedov, N. I. Pridvorev, and V. V. Verzilin, "Recovery of fertility of chernozems by crop rotation," Zemledeleie, No. 4, 5–7 (2003).
4. A. A. Zavalin, O. A. Sokolov, and N. Ya. Shmyreva, "Nitrogen fluxes in agrophytocenosis on soddy-podzolic soil (study with ^{15}N)," Vestn. Ross. S-kh. Nauki, No. 5, **17–21** (2018). https://doi.org/10.30850/vrsn/2018/5/17-21
5. A. A. Zavalin, N. Ya. Shmyreva, O. A. Sokolov, and A. S. Awilow, "The use of nitrogen of white mustard by winter wheat depending on the method of application of nitrogen fertilizers," Zemledeleie, No. 5, 15–17 (2016).
6. A. N. Isakov and V. N. Lukashov, "The role of leguminous grasses and legume-cereal grass mixtures for the creation of a fodder resources and biologization of land farming," Prirodoobustroistvo, No. 3, **105–108** (2018). https://doi.org/10.26897/19976011/20183-105-109
7. V. G. Loshakov, "Green fertilizer as a factor to increase the soil fertility, biologization, and greening of land farming," Plodorodie, No. 2, **26–29** (2018). https://doi.org/10.25680/S19948603.2018.101.09
8. Yu. A. Malysheva, N. V. Polyakova, and N. V. Platonycheva, "The content of organic matter in soil of the links of the crop rotation with green manure crops," Zemledeleie, No. 2, 16–17 (2008).
9. V. I. Mel'nikov, "The main results and prospective development of land farming in Belgorod oblast," Dostizh. Nauki Tekh. APK **33** (1), 4–5 (2019). https://doi.org/10.24411/0235-2451-2019-10101
10. *Practical Guide for Conducting Researches in Long-Term Experiments with Fertilizers*, Ed. by V. D. Pannikov (Pryanishnikov Institute of Agrochemistry, Moscow, 1983), Part 2, p. 52.
11. L. V. Pomazkina, "A new integrated approach to assessment of the functions of agroecosystems and environmental regulation of anthropogenic load, including technogenic soil pollution," Usp. Sovrem. Biol. **124** (1), 66–76 (2004).
12. V. V. Seregin, F. V. Yamyshevskii, and E. A. Muravin, "The use of labeled nitrogen in the plant mass of legumes with different ratios of C : N by barley using a nitrification inhibitor," Agrokhimiya, No. 6, 42–57 (2000).
13. Yu. P. Skorochkin and Z. Ya. Bryukhova, "Green manure fallow and straw are the elements of land farming biologization in the northeastern part of the central chernozemic region," Zemledeleie, No. 3, 20–21 (2011).
14. M. S. Sokolov, "Soil improvement and biologization of land farming are the most important factors for optimization of the ecological status of the agroregion (Belgorod experience)," Agrokhimiya, No. 11, 3–16 (2019). https://doi.org/10.1134/S0002188119110127
15. A. A. Sukov, "Assimilation by plants, fixation in soil and loss of nitrogen from plant residues," Agrokhimiya, No. 6, 12–17 (1979).
16. T. P. Sukhopalova, "Economic efficiency of cultivation of fiber flax after the predecessors with intermediate crops of white mustard," Dostizh. Nauki Tekh. APK **33** (9), 87–90 (2019). https://doi.org/10.24411/0235-2451-2019-10919
17. V. G. Sychev, V. A. Chernikov, O. A. Sokolov, and N. B. Makarov, *Encyclopedic Dictionary on Agrochemis-*

try and Agroecology (Pryanishnikov Institute of Agrochemistry, Moscow, 2019), p. 203.

18. V. Yu. Timonov, N. I. Kartamyshev, and N. M. Chernyshova, "Green fertilizers in crop rotation," Zemledeleie, No. 1, 16–18 (2011).
19. V. A. Chernikov, S. V. Lukin, A. A. Zavalin, N. Ya. Shmyreva, and O. A. Sokolov, "Nitrogen fluxes in agrophytocenosis using organic fertilizers (study with ^{15}N)," Agroekologiya, No. 4, 18–22 (2015).
20. N. Ya. Shmyreva, O. A. Sokolov, and L. N. Tsurikov, "The involvement of nitrogen of perennial grasses in the formation of organic matter in soddy-podzolic soil," Plodorodie, No. 6, 25–27 (2012).
21. L. N. Shchapova, "Microbial succession in organic matter transformation," Eurasian Soil Sci. **37**, 844–852 (2004).
22. G. Cadisch, E. Handuyanto, and N. Malamac, "Recovery from legume prunings and priming effects are governed by the residue quality," Plant Soil **205** (2), 125–134 (1998).
23. T. E. Crews and M. B. Peoples, "Can the synchrony of nitrogen supply and crop demand me improved in legume and fertilizer agroecosystems," Nutr. Cycl. Agroecosyst. **72**, 101–120 (2005). https://doi.org/10.1007/s10705-004-6480-1
24. T. R. A. Denk, K. Butterbach-Bahl, and R. Kiese, "The nitrogen cycle: a review of isotope effects and isotope modeling approaches," Soil Biol. Biochem. **105**, 121–137 (2017). https://doi.org/10.1016/j.soilbio.2016.11.015
25. V. Gaillard, L. Chenu, and S. Recous, "Carbon mineralization in soil adjacent to plant residues of contrasting biochemical quality," Soil Boil. Biochem. **35** (1), 93–99 (2003). https://doi.org/10.1016/S0038-0717(02)00241-9
26. L. S. Jensen, T. Salo, and F. Palmason, "Influence of biochemical quality on C and N mineralization from a broad variety of plant materials in soils," Plant Soil **273** (1–2), 307–326 (2005). https://doi.org/10.1007/s11104-004-8128-y
27. E. Jnselsbacher, W. Wanek, and J. Strauss, "A novel ^{15}N tracer model reveals: Plant nitrate uptake governs nitrogen transformation rates in agricultural soils," Soil. Biol. Biochem. **57**, 301–310 (2013). https://doi.org/10.1016/j.soilbio.2012.10.010
28. A. Hadas, L. Kautsky, M. Goek, and E. E. Kara, "Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover," Soil. Biol. Biochem. **36** (2), 255–266 (2004). https://doi.org/10.1016/j.soilbio.2003.09.012
29. T. D. Hooker and Y. M. Stark, "Carbon flow from plant detritus and soil organic matter to microbes-linking carbon and nitrogen cycling in semi-arid soils," Soil Sci. Soc. Am. J. **76** (3), 903–914 (2012). https://doi.org/10.2136/sssaj2011.0139
30. B. Nicolardot, S. Recous, and B. Mary, "Simulation of C and N mineralization during crop residue decomposition: a simple dynamic model based of the C : N ratio of the residues," Plant Soil **228** (1), 83–106 (2001). https://doi.org/10.2136/sssaj2011.0139
31. C. A. Palm, C. N. Gachengo, and R. J. Delve, "Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database," Agric. Ecosyst. Environ. **83** (1–2), 27–42 (2001). https://doi.org/10.1016/S0167-8809(00)00267-X
32. N. Ya. Shmyreva, O. A. Sokolov, and A. A. Zavalin, "Feature of nitrogen microorganism assimilation of perennial grasses phytomass of a different of erosion soil," Russ. Agric. Sci. **40** (4), 271–274 (2014). https://doi.org/10.31857/S2500-26272019436-38
33. O. A. Sokolov, N. Ya. Shmyreva, and A. A. Zavalin, "Nitrogen utilization by oat plants in agrosystem," Russ. Agric. Sci. **105**, 121–137 (2017). https://doi.org/10.3103/S1068367417040139
34. L. Thuries, M. Pansu, and C. Feller, "Kinetics of added organic matter decomposition in a Mediterranean sandy soil," Soil Biol. Biochem. **33** (7–8), 997–1010 (2001). https://doi.org/10.1016/S0038-0717(01)00003-7.
35. http://www.fedstat.ru/indicators/stat.do. Cited October 20, 2020.

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