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REGULATION OF NITROGEN-CARBON INTERACTIONS IN AGROECOSYSTEMS IN THE FOREST-STEPPE ZONE OF UKRAINE

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Aim. To determine the specified parameters of the complex model of nitrogen-carbon circulation while using different types of crop rotation, kinds of organic fertilizers and ways of soil cultivation in agroecosystems of the forest-steppe zone of Ukraine. **Methods**. Field, laboratory, computational, mathematical and statistical. **Results.** Specific types of organic fertilizers affect the emission of CO_2 into the lowest atmospheric layer: in case of humus the typical emission interval is 25–85 t/ha, while in case of secondary products it is 70–160 t/ha. The impact of the way of chernozem preparation on nitrogen-carbon circulation is manifested in the fact that in case of subsurface tillage the carbon balance in soil was positively increasing compared to ploughing. The interval of CO_2 emission into the lowest atmospheric layer due to the mineralization of humus and organic fertilizers with ploughing changes in a wider range compared against subsurface tillage. **Conclusions**. The nitrogen-carbon interactions are impaired due to the introduction of humus and removal of secondary products beyond the boundaries of the agroecosystem in the course of ploughing. The application of ground secondary products of crop production as organic fertilizers, wrapped up into the surface layer of chernozem during the subsurface tillage of soil, simulates the natural course of nitrogen-carbon circulation in agroecosystems of different types. Natural soil formation process is simulated due to the activation of photosynthetic activity of cultivated crops with CO_2 saturation in the lowest atmospheric layer, which provides for extensive restoration of chernozem fertility in the forest-steppe zone of Ukraine.

Key words: carbon, nitrogen, CO_2, subsurface tillage, deep ploughing, agroecosystem.

INTRODUCTION

The circulation of nitrogen and carbon are the main biochemical cycles, taking place in terrestrial eco- and agroecosystems [1–3]. Recent studies demonstrate that, on the one hand, it is common to include the carbon cycle of the ecosystem into climatic models as an integral characteristic of a carbon cycle – CO_2 concentration in the atmosphere [4, 5]; on the other hand, the deficiency of mineral forms of terrestrial nitrogen has negative effect on the development of autotrophs both in natural systems and in agroecosystems, influencing the depositing of atmospheric carbon which enhances the consequences of global climate changes [2, 6, 7]. The isolation of the nitrogen cycles from the consideration of the consequences of climate changes leads to incomplete estimation of the response of ecosystems and agroecosystems, where mineral forms of nitrogen in soil are the limiting factor for the development of terrestrial plants in nature [8–10] and agroecosystems [11].

There is considerable impact of the nitrogen circulation on the inverse relation between the change in the climate characteristics and the carbon cycle: the higher the dependence of the performance of agro- and natural systems on the amount of assimilated nitrogen in soil, the faster the emission of CO_2 is accumulated by terrestrial plant aggregations [12], thus the complex quantitative estimate of the interaction between the carbon and nitrogen cycles has considerable impact on the process of increasing or decreasing the carbon stocks of terrestrial eco- and agroecosystems [13, 14]. The interdependence and intensity of nitrogen and carbon cycles result in changes in the content of nitrogen and carbon in plants, detritus layer and soil organic matter [1, 15–17] and are the foundation of the natural soil formation in agrosystems using soil-restorative adaptive systems of soil preparation [16].

As a rule, climate warming leads to the decrease in CO_2 depositing in eco- and agroecosystems [18] which is related to the increase in the intensity of both productive and destructive processes: the rate of organic matter decomposition in soil is enhanced, soil breathing is intensified which results in higher dependence of the performance of different plant aggregations on soil humidity and air temperature. In case of excessive manifestation of the abovementioned processes, the intensity of soil breathing starts exceeding the rate of atmospheric CO_2 accumulation by plants, and eco- and agroecosystems transform into the sources of emission of carbon dioxide [17] and nitrous oxide [3, 19] into the atmosphere.

The failure to take the interaction of nitrogen and carbon circulation in the conditions of climate warming into consideration results in the reduction of stocks of terrestrial carbon in plant aggregations (including agroecosystems) and in soil due to the intensification of autotrophic breathing and the rate of the decomposition of organic matter of detritus and soil, i.e. the carbon-climate interaction gets positive direction. The course of the nitrogen cycle reflects on the increase in the terrestrial carbon content due to the increase in the air temperature which is conditioned by the increase in CO_2 concentration in the atmosphere and the intensification of mineralization processes in soil, which results in terrestrial accumulation of available mineral nitrogen, stimulating the performance of eco- and agroecosystems and intensifying the productivity of photosynthesis [11, 20, 21]. In case of a sufficient level of the mentioned processes the need for atmospheric carbon in plant aggregations starts exceeding the emission of carbon in soil, while terrestrial eco- and agroecosystems get transformed into systems – accumulators of atmospheric organic matter, i.e. the carbon-climate interaction becomes an inverse correlation model [2, 14] which diminishes negative manifestations of the greenhouse effect of the climate changes in the forest-steppe of Ukraine.

Therefore, the elaboration of a complex model of the interaction of nitrogen circulation (using different types of crop rotation and kinds of organic fertilizers as well as different methods of chernozem cultivation) and carbon circulation allows estimating carbon circulation with expected climatic changes reliably, determining the main regularities of the direction of nitrogen-carbon circulation, nature and mechanisms of restoring natural soil-formation using soil-restoring adaptive measures in the agroecosystems of the modern climatic system of the forest-steppe of Ukraine.

This work was aimed at determining the specified parameters of the complex model of the interaction between nitrogen circulation and carbon circulation using different types of crop rotation and alternative types of organic fertilizers with different methods of soil cultivationas well as determining the main regularities of the direction of nitrogen-carbon circulation, nature and mechanisms of restoring natural soil formation using soil-restoring adaptive measures in the agroecosystems in the modern climatic system of the forest-steppe of Ukraine.

MATERIALS AND METHODS

The study was conducted in the long-term field stationary experiment of the Cherkasy State Agricultural Experimental station on typical heavy loam, light clay, low humus chernozem with the humus content of 3.8–4.2 %, the content of mobile phosphorus of 12–14 mg per 100 g of soil and mobile potassium – 8–10 mg per 100 g of soil, pH_Q = 6.8–7.0. The area of the seeding bed was 162 m^2, the reporting area – 100 m^2, the experiment was laid down in triplicate. The results for 35 years were rated. Two five-year crop rotations were studied. Crop rotation 1: peas–winter wheat–sugar beets–corn–corn. Crop rotation structure: 60 % of grain crops, 20 % grain legumes, 20 % technical crops. Crop rotation 2: perennial grass–winter wheat–sugar beets–corn–barley with grass. Crop rotation structure: 60 % grain crops, 20 % technical crops, 20 % perennial grass. The system of fertilization: without fertilizers, single dose (one dose – $N_{33}P_{31}K_{41}$) and double dose (two doses − $N_{66}P_{62}K_{82}$) of mineral fertilizers. Until 2000 the mentioned doses of mineral fertilizers were introduced on the background of 6 t/ha of humus with the extraction of secondary products, and in 2001–2010 humus was substituted with 6 t/ha of secondary products. The ways of soil cultivation: different deep ploughing; subsurface tillage, surface tillage. The calculation of carbon balance in the agroecosystems of different types and forecast of the humus condition

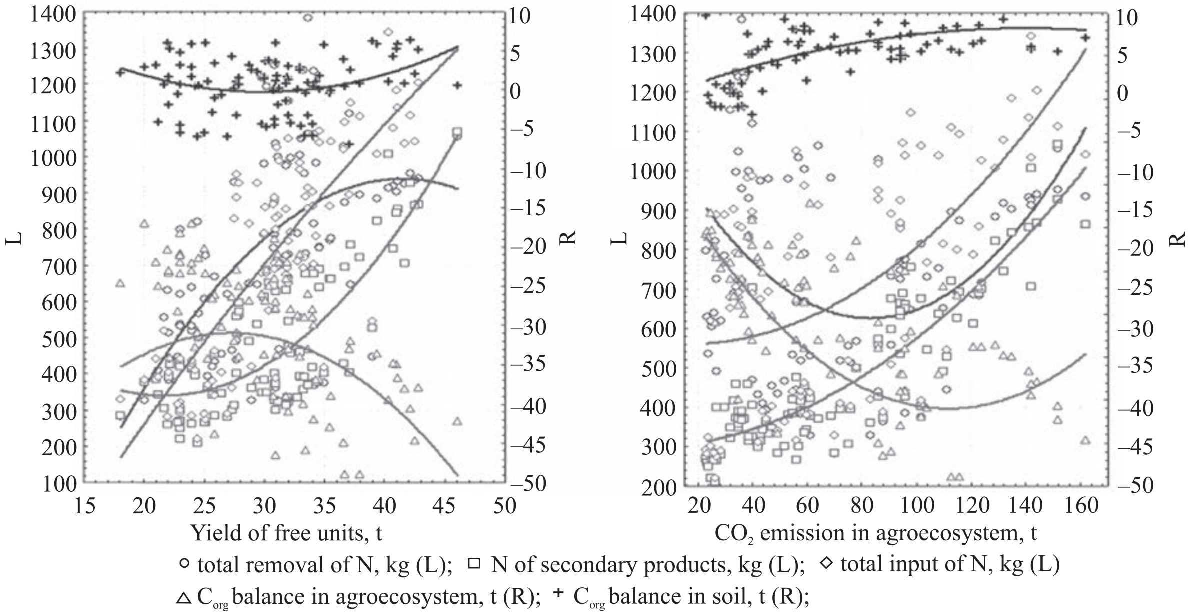


Fig. 1. The general model of nitrogen-carbon circulation in agroecosystems of short-term crop rotations for the forest-steppe of Ukraine

of chernozem as per weight of released CO_2 was performed using the following flows:

C_γ – weight of CO_2, released due to humus mineralization, t;

C_p – weight of CO_2, released due to the mineralization of secondary products, crop and root remains, t;

$C_{(\gamma + p)}$ – total weight of CO_2, released due to mineralization, t;

C_j – weight of CO_2, released via the breathing of soil organisms, t.

The level of ensuring potential bioproductivity of crops with CO_2 resources was determined using the balance of this resource, while the balance of organic carbon was estimated as the difference between the input of C_{org} to the agroecosystem and its introduction from the secondary products or pus into humus. The expenditure item involves the removal of C_{org} with the harvest and the weight of C_{org} of secondary products, which passed to CO_2 due to mineralization. For clarity of calculations C_j was taken as a constant for all the variants. The carbon balance was calculated using the common method taking into account the removal of nitrogen (N) by the level of the performance of crops; it was used as a basis to calculate the balance (N) [22] in the agroecosystems of crop rotation with further elaboration of the recommendations for the official publishing of the 6th National Communication of Ukraine on the Issue of Climate Change, 2012 [18].

RESULTS AND DISCUSSION

The calculations were used to determine the specified average parameters of nitrogen-carbon circulation for the forest-steppe zone (Fig. 1). The average removal N with the harvest (30.6 t of feed units (f.u.) per one crop rotation or 6.12 kg/ha per year) was 596 kg (119 kg/ha) per one crop rotation with typical interval values of 426–718 kg. The total removal of nitrogen from the agroecosystem is 744 kg, and the typical interval removal is 525–937 kg. The input of N due to post-harvest, root, post-mowing remains and humus was 478 kg on average, and 342–634 kg in the interval measurement. The total input of N with the consideration of mineral fertilizers, nitrogen-fixation, N of seed material and rainfall amounted to 715 kg or 424–935 kg in the interval measurement with increasing removal. The balance of N in agroecosystems amounted to 30 kg (–6 kg/ha) and was −203…+163 kg in the interval measurement. The intensity of N balance was 101 %, which was 77–122 % in the interval measurement. The interaction between nitrogen circulation and carbon circulation was established: there is 1.12 t of negative carbon balance per one unit of negative value of nitrogen balance. The negativity of nitrogen balance in agroecosystems ensures the positivity of carbon balance in soil ($B_{C(s)}$) on the level of simple replacement ($B_{C(s)}$ = +0.5 t or $B_{C(s)}$ = 0.1 t/ha, which in the interval measurement is $B_{C(s)}$ = −1.7…−2.9 t. On average the intensity of N balance (I_b) was 101 % or 77–122 %, and I_b (C_{agr}) = 21.5–86 %; in soil I_b (C_{soil}) = 69.5–116 %.

While introducing humus and removing the secondary products from the agroecosystems, the parameters of nitrogen circulation as per the removal of yield were decreased, compared to the average values, down to 551 kg (110 kg/ha) and the interval values were 383–680 kg. Here the total removal of N increased up to 821 kg (164 kg/ha) and in the interval estimates it was 528–1031 kg (106–206 kg/ha). The input of N with afterharvest and root remains decreased by 129 kg (253.8 kg/ha) and the interval value of nitrogen input corresponded to 300–389 kg (60–78 kg/ha).

The total input of N into the agroecosystem was 629 kg (125.8 kg/ha), which is 352–846 kg (70–169 kg/ha) in the interval values. With humus introduction the nitrogen balance in agroecosystems was −203 kg (−41 kg/ha), which was −403…−64 kg or −80.6…−12.8 kg/ha in the interval estimates. The intensity of N balance was 37–91 %, or 82.1 % on average. The increase in the deficiency of N balance with systematic introduction of humus is related to the increase in the deficiency of carbon balance both in agroecosystems ($B_{C(a)}$) and in soil: $B_{C(a)}$ = −28 t ($B_{C(a)}$ = −31.5…−23.0 t, $B_{C(s)}$ = −1.3 t, $B_{C(s)}$ = −4.5…−1.1 t). Here I_b of carbon in the agroecosystem and soil were on the level of 59.4−80.8 %.

With the systematic introduction of secondary products the total removal of N with the harvest compared against the average value increased by 45 t (9 t/ha), and as per interval estimates – by 102–93 t (20.4–18.6 t/ha). The input of N from the secondary products increased by 127 and 174 % against the average value and the systematic introduction of humus, thus it amounted to 607 kg (121 kg/ha) or 425–702 kg (85–140 kg/ha). The total input of N amounted to 802 kg which exceeded the average value and the introduction of humus by 113 and 128 % respectively, and the interval value amounted to 432–1052 kg or 86.4–210 kg/ha. The N balance in agroecosystems was positive (+143 kg or +28.6 kg/ha) which was +44...+272 kg (8.8–54.4 kg/ha) in the interval estimate. The intensity of the balance changed in the range of values from 112 to 130 %. In case of applying secondary products the positivity of N balance in the agroecosystem was accompanied with the increase in the deficiency of carbon balance (B_C(a) = −38.8 t) and the positivity of carbon balance in soil ($B_{C(s)}$ = +2.3 t). Thus, I_b in the first case was 62.1 %, and in the second one − 110 %.

Due to the mineralization processes on average 101 t CO_2 were released into the atmosphere per one crop rotation, while in case of humus introduction it was 2.43 times less, and it was 1.42 times less against the average value.

In the crop rotation with peas (Fig. 2, Table 1) using the secondary products the removal of N with the yield increases by 120 %, and the total removal of N from the agroecosystem decreases by 180 kg (36.0 kg/ha) against the average value. The interval value of the removal of N tapers with the use of the secondary products, and extends with the introduction of humus with the typical interval range of 1.68 (Table 1). With the use of humus the input of N with the secondary products decreases 2.02 times, which is a 3-fold decrease by the typical interval range. The total input of N increases 1.42-fold, which is a 1.27-fold increase by the typical range. In case of applying secondary products the balance of N in the agroecosystem becomes positive (+97.8 kg), while in case of humus the balance of N was negative (–345 kg), which was +32.6 and −55 kg by the typical interval range respectively. The intensity of N balance was 109 and 66.7 % respectively with the 1.62-fold decrease of the typical range using the secondary products. The removal of N with the yield increased by 62 kg or by 113 % in the crop rotation with perennial grass using the secondary products than in case of humus introduction, while the total removal of nitrogen decreased by 129 kg (25.8 kg/ha).

The input of N due to the secondary products in the crop rotation with grass (Fig. 2) was 116 and 20 kg lower compared to the crop rotation with peas in case of humus introduction, but in the framework of the crop rotation with the application of humus the input of N decreased by 183 kg (36.6 kg/ha), which is a 1.58-fold decrease by the typical interval range. In case of introducing the secondary products, the total input of N in the crop rotation with grass decreased 1.14 times and increased 1.13 times in case of humus application compared to the crop rotation with peas, while in the crop rotation with peas the application of secondary products ensured 1.15 times higher input of N compared to humus application.

In the first case the balance of N was +189 kg (37.8 kg/ha), and in the second one it was –61.4 kg (–12.3kg/ha). Thus, in case of applying the secondary products I_b was 1.34 times higher.

The positivity of N balance in case of applying the secondary products does not ensure the positivity of the balance of organic carbon (–38.8 t) in the agroecosystems of crop rotations with peas and grass, whereas the negative balance of carbon was formed in the mentioned crop rotations with the humus introduction and it was 1.30–1.5 times less deficient. However, in case of applying the secondary products the positivity of N

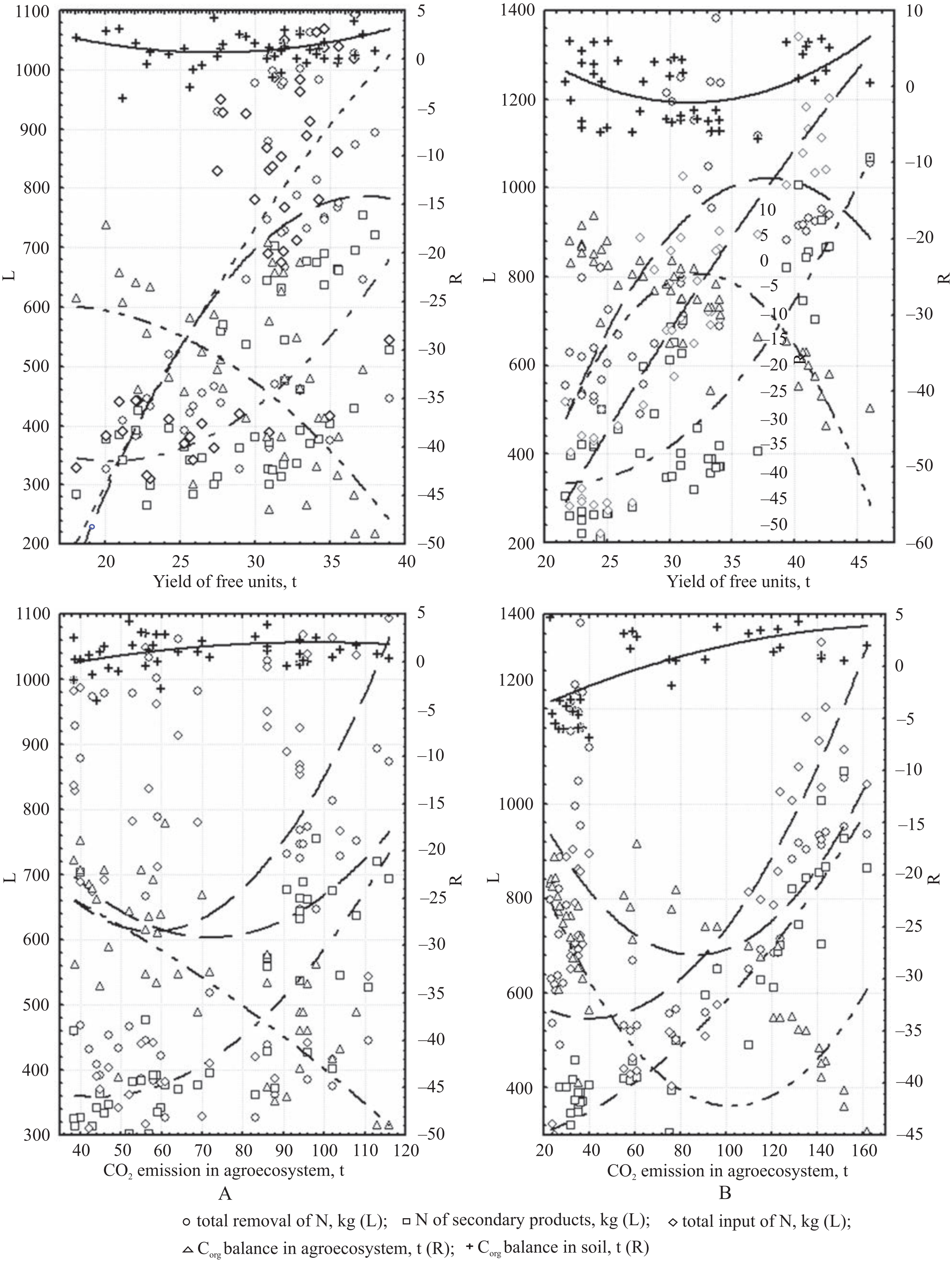


Fig. 2. The general model of nitrogen-carbon circulation in agroecosystems of crop rotations for the forest-steppe of Ukraine: A − crop rotation with grass; B – crop rotation with peas

balance affected the balance of organic carbon in soil (+2.0…−2.7 t or +0.40…−0.54 t/ha) in the crop rotation with peas and perennial grass. With the humus introduction the negativity of N balance determined the negativity of carbon balance in soil; −3.12 t (−0.63 t/ha) in the crop rotation with peas and −0.93 t (−0.06 t/ha) in the crop rotation with perennial grass. Here I_b of carbon in the agroecosystems of crop rotations regardless of the kind of organic fertilizers amounted to 56.6−62.2 %, and I_b of carbon balance in soil for the application of the secondary products in the crop rotation with peas was 114.2 %, and in the crop rotation with perennial grass – 107.6 %. In case of humus introduction in the former case I_b = 59.4 %, and in the latter – 102.6 %, which testifies to the efficiency of applying humus and secondary products specifically with the saturation of crop rotations with perennial grass.

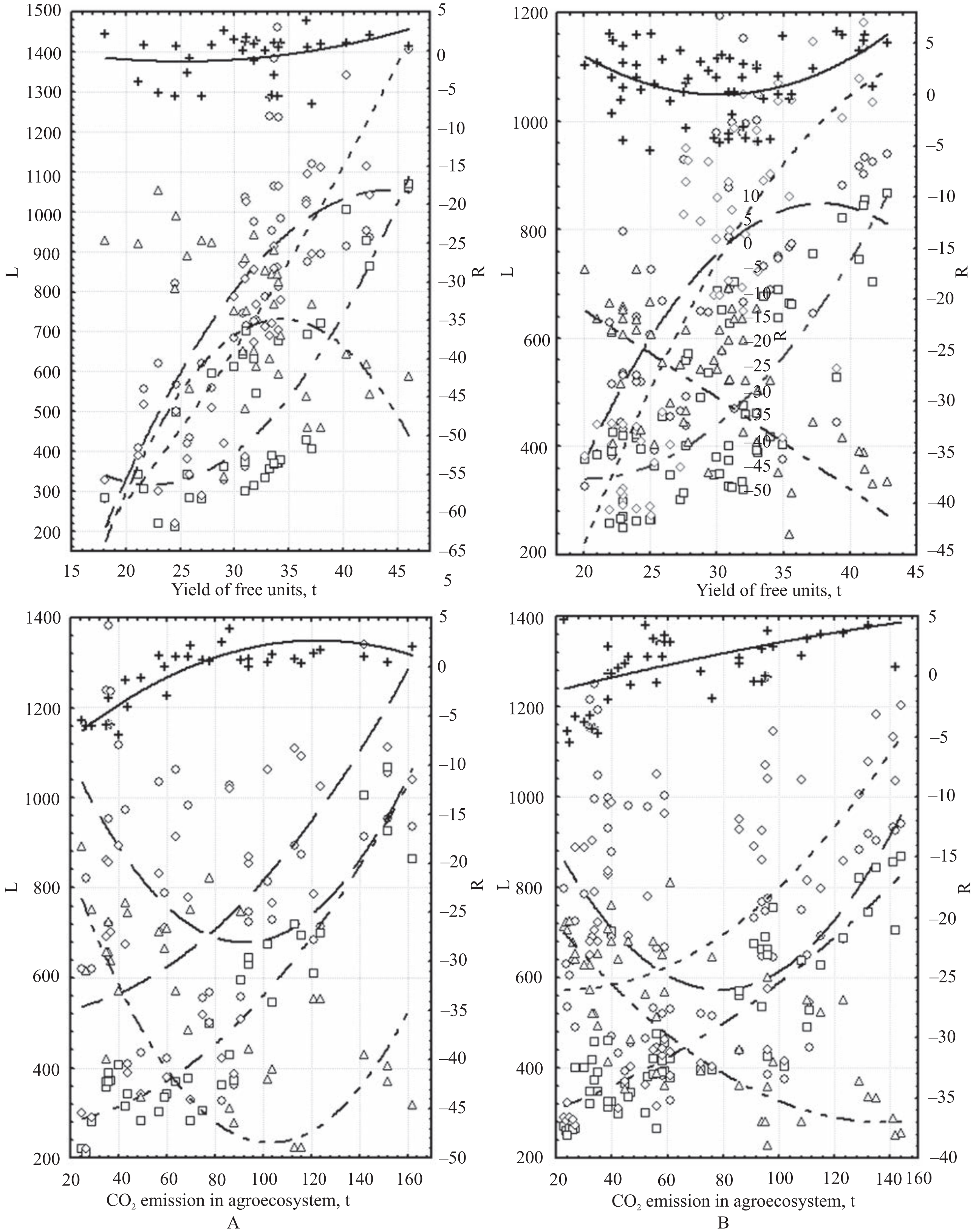
The calculations demonstrate that alongside with the effect of the kind of organic fertilizers and type of crop rotation the kind of soil preparation has its impact on the circulation of N (Fig. 3, Table 2). Thus, with the systematic deep ploughing the removal of N with the yield is 645 kg; with subsurface tillage (20–25 cm)– 628 kg, and with surface tillage (10–12 cm) – 457 kg. According to the typical interval range the removal of N was more stable with the subsurface tillage, whereas in case of deep ploughing and surface tillage the removal of N was 1.24 and 1.23 times higher (Table 2). The total removal of N from the agroecosystem was the highest in case of ploughing (813 kg), while it was 17 and 252 kg or 3.4 and 50.4 kg/ha less for subsurface tillage and surface tillage, respectively. The introduction of N with the secondary products was the same for deep ploughing and subsurface tillage (488 kg) and it was 38 kg lower for surface tillage. The total introduction of N into the agroecosystem for deep deep ploughing was 717–742 kg (143–148 kg/ha), and it decreased by 105 and 80 kg respectively for surface tillage. The balance of N for ploughing and subsurface tillage was negative: −68.4 and −80.4 kg, whereas it proved to be positive for surface tillage – +103 kg (+20.6 kg/ha).

The balance intensity for deep ploughing was 94.1−94.6 %, and for surface tillage – 122 %. The intensity of carbon balance in the agroecosystem and soil was

Table 1. The impact of a crop rotation and a kind of organic fertilizers on the specified parameters of nitrogen-carbon circulation in the agroecosystems of the forest-steppe of Ukraine

Parameter of circulation	Crop rotation with peas				Crop rotation with grass			
	Humus, 6 t/ha		Secondary products, 6 t/ha		Humus, 6 t/ha		Secondary products, 6 t/ha	
	X_{aver}	Interval	X_{aver}	Interval	X_{aver}	Interval	X_{aver}	Interval
Yield of feed units, t	29.0	24.8−33.3	33.0	25.3–41.0	29.3	25.8–32.4	30.7	27.8–35.3
Nitrogen removal with the yield, kg	601	501–721	718	551–895	502	356–644	564	370–718
Total removal of nitrogen, kg	92.5	634–1204	745	563–921	717	450–981	588	384–749
Input of N, kg:								
secondary products	330	265–389	665	473–849	366	314–387	549	379–669
N in the agroecosystem, kg	591	291–824	837	505–1096	667	387–875	767	441–1038
Nitrogen balance, kg (±)	−345	−535…−215	+97.8	−64−188	−61.4	−176…−406	189	55.5–305
I_b in the agroecosystem, %	66.5	47.0–76.0	109	89–124	97.0	79.0–95.5	130	115–137
Balance of C_{org} of the agroecosystem, t	−25.8	−29.0…−22.5	−38.7	−38.0…−25.0	−30.2	−33.5…−23.8	−38.8	−46.3…−33.0
Balance of C_{org} of soil, t	−3.12	−5.88…−3.31	+2.7	+0.9…+4.0	–0.93	–0.63…–1.62	2.00	0.4–2.7
I_b of C_{org} of the agroecosystem, %	62.2	14.0–92.0	62.0	26.0–85.0	56.6	18.5-85.0	62.2	23.0–85.5
I_b of C_{org} of soil, %	59.4	54.0–65.0	114.2	109–129	102.2	94.5–112.5	107.6	103–117
C_{org} (CO_2), t	30.8	26.0–35.0	111	77.0–142	52.3	42.6–58.9	91.5	86.0–102

Note. X_{aver} − average value.



○ total removal of N, kg (L); □ N of secondary products, kg (L); ◇ total input of N, kg (L);
△ C_{org} balance in agroecosystem, t (R); + C_{org} balance in soil, t (R)

Fig. 3. The general model of nitrogen-carbon circulation in agroecosystems of crop rotations for the forest-steppe of Ukraine: A – deep ploughing; B – subsurface tillage

under 100 % regardless of the way of soil cultivation: 55.3–62.7 % for carbon in the agroecosystems and 93.5–98.2 % for carbon in soil. Here CO_2 emission due to the mineralization of the organic matter demonstrates a stable tendency towards the decrease, caused by ploughing (CO_2 – 77.5 t or 15.5 t/ha), compared to subsurface tillage (67.9–68.5 t or 13.5 t/ha) and 60.2 t (12.4 t/ha) for surface tillage. There was an ambiguous effect of the way of soil cultivation on the amount of NO_2 emission: 21–23 kg (4.2–4.6 t/ha).

The estimates demonstrated (Table 3) that the kind of organic fertilizers affects the correlation level between the yield of feed units and the components of the nitrogen balance. In case of humus introduction there was a direct correlative relationship between the performance of crop rotations, the total removal of nitrogen, its input from the secondary products and the total input of N: R = 0.69 ± 0.02; R = 0.57 ± 0.03, R = 0.87 ± 0.02 and R = 0.82 ± 0.02 respectively, whereas in case of introducing the secondary products the relationship enhanced up to the level of direct strong correlation: R = (0.82–0.88) ± 0.03. Here with the increase in the performance of crop rotations using humus introduction the balance of organic carbon in the soil was negative, whereas in case of introducing the secondary products it was positive in the whole interval of the typed performance. In the latter case one unit of performance increase had 2.1 times smaller amount of the removal of total nitrogen, and the input of nitrogen from the secondary products was 2.13 times higher than in case of humus application.

In case of humus introduction the relationship between CO_2 emissions due to mineralization and the input of nitrogen corresponded to the level of weak correlation (R = 0.28–0.30 ± 0.05), whereas in case of introducing the secondary products it was on the level of direct strong correlative dependence (R = 0.79–0.85 ± 0.02), while the unit of CO_2 released from the mineralization of the secondary products had 5.59 and 8.44 kg/ha of N of secondary products and nitrogen of general input.

In case of applying the secondary products the balance of C_{org} in soil was positive in the typed interval of CO_2 emission, whereas with the humus introduction the positivity of carbon balance was accompanied with the deficiency of nitrogen balance in the typed interval of CO_2 emission due to mineralization. Direct correlation was established between the performance of a crop rotation with peas, the total removal of nitrogen, the introduction of nitrogen from the secondary products, total nitrogen introduction and the nitrogen removal on the level of R = 0.57 ± 0.03, with nitrogen input – on the level of R = (0.79–0.91) ± 0.03. In a crop rotation with grass the relationship between the performance and components of nitrogen balance weakens down to the average level by the removal and input of nitrogen from the secondary products R = (0.58–0.61) ± 0.03,

Table 2. The impact of the ways of soil preparation on the specified parameters of nitrogen-carbon circulation in the agroecosystems of the forest-steppe of Ukraine

Parameter of circulation	The way of soil cultivation					
	Deep ploughing		Subsurface tillage		Surface tillage	
	X_{aver}	Interval	X_{aver}	Interval	X_{aver}	Interval
Yield of feed units, t	31.7	27.4–34.2	31.0	27.0–34.6	28.1	23.5–31.6
Nitrogen removal with the yield, kg	645	646–732	628	514–723	47.5	371–518
Total removal of nitrogen, kg	813	593–1005	796	650–979	561	452–648
Input of N, kg:						
secondary products	488	339–638	488	340–657	450	371–525
N in the agroecosystem, kg	742	461–966	717	452–907	637	376–966
Nitrogen balance, kg (±)	–68.0	–215…+115	–80.4	–245…+149	103	–93.0…+334
I_b in the agroecosystem, %	94.6	77.5–117	94.1	71.0–122	122	83.0–102
Balance of C_{org} of the agroecosystem, t	–39.8	–42.1…–26.9	–29.5	–34.1…–22.1	–27.3	–33.0…–22.0
Balance of C_{org} of soil, t	–0.75	–3.7…+1.2	1.4	–0.5…+3.8	0.7	–0.6…+2.8
I_b of C_{org} of the agroecosystem, %	62.7	21.5–87.5	55.3	21.0–85.0	57.8	22.0–84.0
I_b of C_{org} of soil, %	93.9	71.0–110	97.3	69.0–127	93.6	59.0–116
C_{org} (CO_2), t	77.5	41.5–103	67.9	35.0–69.9	60.2	33.0–86.0

and there is an established direct strong correlation between the total input of nitrogen and performance of crops (R = (0.73−0.83) ± 0.02); this dependence weakens to the weak level with the nitrogen balance (R = = (0.82−0.87) ± 0.03). The same amount of nitrogen is accounted for by the unit of increasing the crop performance in the crop rotations regardless of the way of soil preparation. In both cases the balance of C_{org} in soil was positive, and the balance of C_{org} in agroecosystems got impaired and, thus, deficient.

Table 3. The values of correlation coefficients and regression coefficients of linear equations of nitrogen-carbon circulation depending on the components of the cultivation system in the agroecosystems of the forest-steppe of Ukraine

Type of crop rotation, kind of organic fertilizers, way of soil preparation	N balance, kg		
	Total removal from the agroecosystem	Entered the agroecosystem	
		with secondary products	total
Yield of feed units in a crop rotation, t Introduction of 6 t/ha of secondary products			
Crop rotation with peas	0.85/12.9*	0.88/48.4	−0.01/−0.33
Crop rotation with perennial grass	0.37/7.90	0.86/53.6	0.13/5.9
Introduction of 6 t/ha of humus			
Crop rotation with peas	0.94/24.5	0.94/37.4	0.77/15.3
Crop rotation with perennial grass	0.29/2.60	0.26/4.80	–0.06/–0.56
CO_2 emission in a crop rotation, t Introduction of 6 t/ha of secondary products			
Crop rotation with peas	0.78/10.7	0.79/40.7	–0.17/–8.93
Crop rotation with perennial grass	0.03/0.21	0.13/2.91	–0.11/–1.82
Introduction of 6 t/ha of humus			
Crop rotation with peas	0.91/5.55	0.93/8.80	0.83/3.88
Crop rotation with perennial grass	0.66/5.59	0.62/10.6	0.35/2.78
Yield of feed units in a crop rotation, t			
Ploughing for 22–25 cm	0.73/23.2	0.83/40.7	0.32/14.8
Subsurface tillage for 22–25 cm	0.75/22.0	0.81/39.5	0.37/17.8
Surface tillage for 10–12 cm	0.72/18.7	0.79/22.4	0.82/46.6
CO_2 emission in a crop rotation, t			
Ploughing for 22–25 cm	0.87/4.48	0.59/4.65	0.66/4.94
Subsurface tillage for 22–25 cm	0.85/4.08	0.53/4.26	0.58/4.55
Surface tillage for 10–12 cm	0.76/3.61	0.52/4.90	0.32/2.60
Yield of feed units in a crop rotation, t (general model)			
Crop rotation with peas	0.57/21.8	0.79/26.9	0.91/42.2
Crop rotation with perennial grass	0.61/28.5	0.58/16.6	0.74/39.1
CO_2 emission in a crop rotation, t (general model)			
Crop rotation with peas	–0.04/–0.19	0.94/4.53	0.72/4.7
Crop rotation with perennial grass	0.03/0.34	0.71/4.35	0.39/4.36
Yield of feed units in a crop rotation, t (general model)			
6 t/ha of humus	0.69/47.1	0.57/10.7	0.87/51.2
6 t/ha of secondary products	0.82/23.2	0.88/22.7	0.82/35.1
CO_2 emission in a crop rotation, t (general model)			
6 t/ha of humus	0.28/1.61	0.30/5.56	0.48/6.51
6 t/ha of secondary products	0.85/5.59	0.79/8.44	0.48/2.64

*Correlation coefficients (R)/regression coefficients (b) in linear equations of dependencies between the parameters.

The estimation of the effect of the way of soil preparation on the relationship between the crop performance in the agroecosystems of short-time rotations and the components of nitrogen balance demonstrates that regardless of the way of soil cultivation there are relationships between the total removal and input of nitrogen from the secondary products on the level of direct strong correlation (R = (0.73–0.83) ± 0.02), whereas the dependence on the total removal of nitrogen weakens down to the weak correlative relationship (R = (0.32–0.37) ± 0.02).

The direct strong correlation (R = (0.85–0.87) ± ± 0.03) was established between nitrogen input from the secondary products and the amount of CO_2 regardless of the way of soil cultivation, and with the total input of nitrogen and its balance the relationship weakens down to R = (0.55–0.65) ± 0.03, which testifies to the decrease in the effect of the ways of chernozem preparation on the relationships between the components of nitrogen-carbon cycle in the agroecosystems of different crop rotations. The types of organic fertilizers as well as a crop rotation have the greatest effect on the nitrogen-carbon circulation, while the way of soil cultivation is a subordinate factor in the agroecosystems. The production of CO_2 depending on the type of a crop rotation is related to the total input of nitrogen (R = (0.71–0.94) ± 0.03), and the balance of nitrogen in the crop rotation with peas correlates with the performance on the level of a direct strong correlation (R = 0.72 ± 0.03), whereas this relationship weakens in the crop rotation with grass (R = 0.45 ± 0.03).

The determination of the effect of the crop rotation factor on the balance of C_{org} in soil demonstrates that the crop rotation with grass has the positivity of the balance in the typed interval of CO_2 emission; there was an increasing tendency of the balance of C_{org} in the crop rotation with peas, and the positivity of the balance of C_{org} in soil is achieved due to the maximal input of nitrogen from the secondary products and the total input, which simultaneously decreases the deficiency of C_{org} of the agroecosystem down to −30 t/ha. There is an increase in the deficiency of C_{org} balance in the agroecosystem due to the removal of the weight of perennial grass in the crop rotation with grass.

The amount of CO_2 released from the mineralization of the organic matter is a direct function of the input from the secondary products (R = (0.85–0.87) ± 0.02), while the relationship with the total input of nitrogen to the agroecosystem and the balance of N weakens to the direct correlation of the medium level (R = (0.53–0.66) ± ± 0.02). The regression coefficients in the linear equations decreased 1.21–1.79 times between the total removal and input of nitrogen, and increased 3.15 times with the total input. The amount of CO_2 released due to the mineralization with the surface tillage correlates with the components of the nitrogen balance in the way, similar to that of deep ploughing, but according to the regression coefficients of the dependence equations one unit of CO_2 emission is accounted for by a 1.25 times smaller amount of nitrogen from the secondary products and a 1.9 times smaller change in the nitrogen balance. The regression coefficients were similar in the values in the regression equations of the dependence of crop rotation performance and CO_2 emissions on the components of nitrogen balance, which testifies to the uniformity of the impact of the way of soil cultivation in the mentioned processes of biogenic element circulation. In case of systematic surface tillage the yield of feed units per 1 ha in the agroecosystems of crop rotations (similar to deep ploughing) is related to the total removal and input of nitrogen via strong direct correlation (R = (0.72–0.79) ± 0.02). Contrary to deep ploughing the level of a correlative relationship between the performance and the total removal of N increased up to the strong direct correlation.

The use of secondary products as organic fertilizers with the localization of the former at the subsurface and systematic surface tillage simulates natural circulation of the organic carbon in agroecosystems, which in the long run promotes the restoration of the resources of C_{org} both in the agroecosystem and in soil, bringing its content closer to the natural status [19, 23]. It was also demonstrated in the works [19, 23] that the total emission of CO_2 decreases in the following order: wild land–fallow–tillage. In spring and summer the emission of CO_2 on the wild land exceeds the emission of carbon dioxide for tillage 10–23 times, also in spring the emission of CO_2 is 10–25 times higher than in autumn with the maintenance of wild land and fallow and 4–5 times higher – in case of systematic tillage in the long run.

The interaction between carbon and nitrogen circulation in the agroecosystems has a considerable impact on the content of nitrogen and carbon in the cultivated crops, detritus and organic matter of soil, and the intensity of nitrogen and carbon circulation is determined by the C to N ratio both in soil and agroecosystems in general [18]. The use of different types of organic fertilizers tells both on the removal of nitrogen and carbon. With humus introduction the removal of nitrogen beyond the boundaries of agroecosystems exceeds its input by 154 kg, whereas, vice versa, in case of applying the secondary products the input of nitrogen into the agroecosystem exceeds its removal by 145 kg due to the input of nitrogen from the secondary products, which increases 1.75 times with humus introduction. Thus, the removal of C_{org} with the introduction of the secondary products increases by 7.6 t, and the input of C_{org} increases 2.1 times compared to the application of humus (Table 4).

Regardless of the kind of organic fertilizers, the amount of nitrogen from 1424 to 1468 kg is involved in the agroecosystems of crop rotations with the increase in case of introducing secondary products, and in the latter case there is 1.48 times more carbon than for humus introduction. The C to N ratio for the total removal using the secondary products was 97 to 1 against 45 to 1 on average with humus introduction, and by the articles of input the C to N ratio was 53 to 1 and 28 to 1. In the general circulation it was 54 to 1 and 37 to 1, respectively. The impact of the type of crop rotation on the C to N ratio has some specificities: the total removal of nitrogen was 1.19 times higher in the crop rotation with peas compared to the crop rotation with grass. The input of nitrogen from the secondary products was 1.1 times higher; the total input – 1.05 times higher, and the amount of nitrogen in the total circulation – 1.15 times higher compared to the crop rotation with grass.

In the crop rotation with peas the removal of C_{org} from the agroecosystems, regardless of their type, was 36.0−39.0 t, and the input of C_{org} was 1.23 times higher though the total amount of C_{org} in the agroecosystems with peas and grass was in the range of 59.4−60.8 t. The C to N ratio in terms of removal from the crop rotation with grass was 1.53 times higher. The input of nitrogen and carbon was registered in the range of 39.5–41.7 t regardless of the type of agroecosystem, though the volume of the total circulation of C and N in the crop rotation with grass was 1.24 times higher compared to the crop rotation with peas. The impact of the way of soil cultivation on the circulation of N was manifested in the fact that with subsurface/surface tillage the total removal, input and volume of N in the agroecosystems decreased 1.05, 1.03 and 1.09 times respectively, while the input and total amount of C_{org} had a stable tendency towards decreasing 1.14, 1.12 times. It affected the C to N ratio, the value of which for subsurface/surface tillage decreased 1.05, 1.08 times against tillage, respectively, compared to the application of humus and straw with tillage, which testifies to the decrease in the intensity of C and N circulation with surface tillage both in soil and agroecosystem in general. A higher amount of reliable correlative inverse relationships between the C

Table 4. The ratio of carbon and nitrogen in agroecosystems of different types using different types of organic fertilizers and ways of chernozem preparation

Parameter of circulation	X_{aver}*	Interval *	X_{aver}*	Interval *
Types of organic fertilizers				
	Humus, 6 t/ha		Secondary products**	
C_{org} (removal) to N (removal)	44.7	34.0–49.0	67.4	52.0–75.0
C_{org} (input) to N (input)	28.0	17.5–39.5	53.2	37.0–64.0
C_{org} (agroecosystem) to N (agroecosystem)	36.9	27.5–40.5	54.2	38.0–57.0
Crop rotation with				
	Peas		Grass	
C_{org} (removal) to N (removal)	44.3	34.0–53.5	67.8	45.0–76.5
C_{org} (input) to N (input)	41.7	18.0–58.5	39.5	28.5–44.5
C_{org} (agroecosystem) to N (agroecosystem)	40.6	27.5–52.5	50.5	34.5–63.5
The way of soil cultivation				
	Ploughing for 22–25 cm		Subsurface for 22–25 cm	
C_{org} (removal) to N (removal)	57.7	41.0–56.5	55.1	41.0–60.0
C_{org} (input) to N (input)	42.4	33.5–54.0	39.0	23.5–57.0
C_{org} (agroecosystem) to N (agroecosystem)	47.7	35.5–54.0	44.3	32.5–53.5

*C_{org}, t per 1 kg of N, **7 t/ha of secondary products.

to N ratio of the abovementioned articles of nitrogen and carbon articles was revealed using different kinds of organic fertilizers: R = (−0.55…−0.81) ± 0.02 for humus introduction and R = (−0.56…−0.73) ± 0.02 for the introduction of secondary products.

For different ways of soil cultivation the level of correlative relationships decreased down to a weak inverse correlation with the removal and input of nitrogen with tillage, and there was a considerable strengthening of the correlative relationship between the removal and total circulation of C and N as well as their ratio: R = (−0.65…−0.73) ± 0.02. In case of surface tillage the inverse reliable correlative relationships were revealed relative to the total circulation of C and N and their ratio, and the strengthening of the relationship to the values of the medium level – relative to the total removal of nitrogen. In the crop rotation with peas the relationships between the mentioned parameters of the nitrogen-carbon circulation were on the level of a weak inverse correlation, and in the crop rotation with grass they approximated the level of values of R = (−0.55…−0.77) ± 0.02. The emission of CO_2 due to mineralization of C_{org} in the agroecosystems was 10.9–14.9 t according to the normalized interval of values with the increase up to 16.7 t with the introduction of secondary products. The emission of CO_2 due to mineralization of secondary products was 3.85−6.83 times higher compared to humus mineralization and amounted to 41.4−102 t, increasing to 139 t by the maximally typical value. The share of CO_2 emission due to mineralization of humus and secondary products was from 74 to 85 %, and reached 89−90 % in its maximal values.

CONCLUSIONS

The circulation of nitrogen, which is one of the main limiting factors of the manifestation of performance and intensity of the destructive processes in the agroecosystems of different crop rotations, has a considerable impact on the circulation of organic carbon with the application of different types of organic fertilizers and ways of chernozem preparation in the climatic system of the forest-steppe of Ukraine.

The use of humus as an organic fertilizer creates the conditions when the total removal of nitrogen from the agroecosystems exceeds its input in the typical interval of the performance increase which is related to the increasing deficiency of the organic matter of humus with excessive mineralization and removal of nitrogen. In case of applying the secondary products the total removal of nitrogen from the agroecosystems is less than its input from the secondary products and mineral fertilizers which improves the balance of the organic carbon in soil and causes the reduction of its deficiency in the agroecosystem in general.

The types of organic fertilizers affects the emission of CO_2 due to mineralization into the atmosphere: according to the typical interval estimate the amount of emission in case of humus application corresponds to 25–85 t, whereas in case of introducing the secondary products the weight of emission reaches up to 80–160 t which is accompanied with the increased removal of nitrogen compared to its input into the agroecosystems in the former case, and vice versa, linearly to the increasing input of the total nitrogen relative to its removal due to mineralization of the secondary products – in the latter. At the same time there is increasing deficiency in the carbon balance in soil with the humus application and the increase in its positivity in case of applying secondary products, i.e. there is extensive restoration of chernozem fertility due to surface tillage.

The impact of the type of agroecosystem (crop rotation) on nitrogen-carbon circulation manifests itself in the fact that the saturation of crop rotations using crops with a high yield of secondary products (crop rotation with peas) ensures linear increase in the nitrogen input in the typical interval measurements of increasing the performance due to the mineralization of secondary products and nitrogen removal from them. The rate of removal and input of nitrogen gets leveled with the removal of the weight of perennial grass, and with the maximal performance they are not compensated with remaining secondary products and nitrogen-fixing, which results in the increase in the deficiency of the carbon balance with the inverse linear dependence whereas in the crop rotation with peas the increase in the carbon deficiency changes parabolically in the typical interval of performance increase. In the latter case the increased emission of CO_2 is accompanied with the increasing carbon balance of soil and the increased performance of the agroecosystem.

The effect of the way of chernozem preparation on the nitrogen-carbon circulation manifests itself in the fact that regardless of the type of organic fertilizers and that of agroecosystem in case of surface tillage the carbon balance in the interval of increasing performance is positively increasing compared to ploughing, where the increase in the deficiency is parabolic. The interval of CO_2 emission into the atmosphere due to mineralization after ploughing was wider relative to surface tillage, which testifies to the increase in the mineralization processes in soil with the uniformity of nitrogen-carbon circulation and determines the way of soil cultivation as a subordinate regulatory subsystem of the crop rotation type and the kind of organic fertilizers in the general circulation.

The introduction of humus and removal of secondary products from the agroecosystem while deep ploughing leads to the balance between nitrogen-carbon circulation which is accompanied with the decrease in the stocks of terrestrial carbon in the agroecosystem and its components (plants, soil, pool of microorganisms). It leads to the intensification of autotrophic breathing and the acceleration of the rate of detritus and humus decomposition i.e. the relationship between carbon circulation and climate becomes positive. In case of this model of agroecosystem maintenance the replacement of ploughing with surface tillage only increases the processes of humification of the organic matter in soil and somewhat improves the impact of the nitrogen-carbon circulation on the year to year variations in the surface heat resource due to the emission of CO_2 from the agroecosystem into the atmosphere.

The application of secondary products as an organic fertilizer enhances the process of optimizing the nitrogen-carbon circulation in agroecosystems of different types towards natural organization which leads to the increase in the stocks of surface carbon with the enlargement of heat resources, conditioned by the increased emission of CO_2 into the atmosphere due to mineralization of the excess of the secondary products and the release of mineral forms of nitrogen into soil. The latter increases the performance of agroecosystems due to the “stimulating effect of N” and enhanced adsorption of CO_2 of the atmosphere. In these conditions the growth of the greenhouse effect promotes the accumulation of organic carbon in agroecosystems and farming ecosystems which get the properties of wastewater systems, i.e. the higher dependence of the performance of agroecosystems on the intensity of nitrogen assimilation which entered the system of a farming ecosystem, the faster the emission of CO_2 due to the mineralization is consumed.

The maintenance and application of ground secondary products of crop production, sufficiently compensated in terms of nitrogen using mineral fertilizers, as organic fertilizers, and wrapped up into the surface layer of chernozem during the surface tillage, simulates the natural course of nitrogen-carbon circulation in agroecosystems of different short-term crop rotations. Here the simulation of natural soil formation in agroecosystems alongside the microbiological activity is ensured by the activation of the photosynthetic activity of cultivated crops due to the restoration of drain mechanisms of carbon with the increase in the CO_2 content in the atmosphere and the accumulation of heat resources in the agroecosystems in general which should be the foundation of extensive restoration of the fertility of typical chernozem of the forest-steppe of Ukraine.

Управління азотно-вуглецевим обігом в агроценозах Лісостепу України

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Мета. Встановити нормативні параметри комплексної моделі обігу азоту і вуглецю при застосуванні різних типів сівозмін, видів органічних добрив і різних способів обробітку ґрунту в агроценозах Лісостепу України. **Методи.** Польовий, лабораторний, розрахунковий, математико-статистичний. **Результати.** Вид органічного добрива впливає на емісію CO_2 в приземний шар атмосфери локалізації стеблостою культур: за використання гною типовий інтервал викидів вуглекислоти становить 25–85 т/га, тоді як при застосуванні побічної продукції – 70–160 т/га. Вплив способу обробітку чорнозему на азото-вуглецевий обіг зводиться до того, що за безполицевого обробітку баланс вуглецю у ґрунті був додатно-зростаючим порівняно з оранкою. Інтервал емісії CO_2 в приземний шар атмосфери від мінералізації гумусу і органічних добрив за оранки змінюється у більш широкому діапазоні відносно безполицевого обробітку. **Висновки.** За внесення гною та вилучення побічної продукції за межі агроценозу за оранки порушується виваженість в азотно-вуглецевому обігу. Використання як органічного добрива подрібненої побічної продукції рослинництва, яка за безполицевого обробітку загортається у поверхневий шар чорнозему, моделює природний характер азотно-вуглецевого обігу в агроценозах сівозмін різного типу. При цьому посилюється природне ґрунтоутворення за рахунок активізації фотосинтетичної активності сільськогосподарських культур при насиченні CO_2 приземного шару атмосфери локалізації стеблостою у період вегетації, що забезпечує розширене відтворення родючості чорноземів Лісостепу України.

Ключові слова: вуглець, азот, CO_2, безполицевий обробіток, оранка, агроценоз.

Управление азотно-углеродным кругооборотом в агроценозах Лесостепи Украины

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Цель. Установить нормативные параметры комплексной модели кругооборота азота и углерода при различных севооборотах, видах органических удобрений и способах обработки почвы в агроценозах Лесостепи Украины. **Методы.** Полевой, лабораторный, расчетный, математико-статистический. **Результаты.** Вид органического удобрения влияет на эмиссию CO_2 в приземный слой атмосферы: при использовании навоза типичный интервал выбросов составляет 25‒85 т/га, тогда как при применении побочной продукции – 70‒160 т/га. Влияние способа обработки чернозема на азотно-углеродный кругооборот сводится к тому, что при безотвальном рыхлении баланс углерода в почве сохранен как положительно-нарастающий по сравнению со вспашкой. Интервал эмиссии CO_2 в приземный слой атмосферы от минерализации гумуса и органических удобрений при вспашке изменяется в более широком интервале относительно безотвального рыхления. **Выводы.** При внесении навоза и изъятии побочной продукции за пределы агроценоза при вспашке нарушается взаимосвязь в азотно-углеродном обороте. Использование в качестве органического удобрения измельченной побочной продукции, которая заделывается в поверхностный слой чернозема при безотвальном рыхлении, моделирует природный характер азотно-углеродного обмена в агроценозах различного типа. При этом моделируется природное почвообразование за счет активизации фотосинтетической активности сельскохозяйственных культур при насыщении CO_2 приземного слоя атмосферы локализации стеблестоя, что обеспечивает расширенное восстановление плодородия черноземов Лесостепи Украины.

Ключевые слова: углерод, азот, CO_2, безотвальное рыхление, вспашка, агроценоз.

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