

CHANGES IN THE BALANCE OF HUMUS IN THE SOIL OF FIVE-FIELD CROP ROTATION DEPENDING ON FERTILIZER SYSTEMS

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Abstract

Studies conducted on deep, medium-loamy typical chernozem within a long-term five-field crop rotation have shown that the removal of all by-products from the fields (soybean, winter wheat, sunflower, spring barley, and grain corn), regardless of the fertilisation system, leads to a negative humus balance ranging from 551 to 1305 kg/ha. When only wheat and barley straw is removed, the humus balance also remains negative across all experimental variants, but at significantly lower levels—ranging from 179 to 277 kg/ha. In contrast, when all by-products of the crops in rotation are used as organic fertiliser, the humus balance becomes positive, amounting to 8–398 kg/ha. The main source of humus formation in the soil is the crop residues of cultivated plants in the rotation. Through their humification, 1.66 times more humus is formed compared to that derived from the by-products of the three main crops. According to the index of agricultural ecologisation and the applied rates of organic fertilisers, the rotation variant in which by-products are used as organic fertiliser and 16 t/ha of manure + $N_{112}P_{100}K_{86}$ is applied qualifies as having an intensive level of agricultural ecologisation. The productivity of the crop rotation in which all crop by-products are removed from the fields is 11–13% lower than that of the rotation where by-products are used as organic fertiliser in three fields.

Key words: crop rotation, soil, humus, balance, fertilisers, yield, dry matter, root residues, post-harvest residues

INTRODUCTION

Soil fertility and balance cannot be maintained without the presence of organic matter and the addition of new amounts of plant residues or chemical and organic fertilizers, as plants extract significant amounts of nutrients from the soil each year. Therefore, manure application can be considered a good source of increasing potential soil fertility [3].

Soil organic matter comprises humus (on average 85%), plant residues (10%), and soil flora and fauna (5%) [22]. In chernozem soils, 95–98% of nitrogen, nearly 60% of phosphorus, and 80% of sulphur are concentrated in humus [23]. Between 50–60% of the nitrogen removed with the biomass of agricultural crops originates from humus that is, nitrogen compounds formed as a result of humus mineralisation (the remaining nitrogen

is supplied by fertilisers, precipitation, plant residues, and biological nitrogen fixation) [20]. In mineral soils, most of the humus is associated with inorganic materials, particularly clays, and these interactions influence both organic and inorganic components. The binding of organic molecules to minerals is commonly studied using adsorption isotherms, where the amount of sorbed organic compound is plotted against its equilibrium concentration remaining in solution. The content of organic matter in soils depends on the availability of organic substrates to the “hungry” microbial population [16].

In natural phytocoenoses, unlike agrocenoses, the issue of organic matter deficiency in the soil does not arise: here, the processes of organic matter synthesis consistently prevail over its decomposition. Humus deficiency in

the soil remains one of the predominant problems in agricultural production. This is primarily due to the high proportion (65–70%) of crop by-products being removed from the fields, the increasing intensity of mineralisation processes in soils, and other pathways of organic matter loss (such as erosion, deflation, and leaching), along with the high concentration of row crops and the near-total absence of perennial grasses [17, 18].

The main strategies for compensating humus content in the soil include the use of all types of organic fertilisers, crop by-products, and green manure; the cultivation of perennial grasses; reducing the proportion of row crops in crop rotations; and minimising mechanical soil tillage [9]. Plant residues can compensate for 24–40% of soil humus losses. Therefore, the incorporation of crop by-products and green manure into humus-restoring processes is of great importance. Moreover, the use of crop by-products, particularly straw, as organic fertiliser has significant ecological value [8, 19].

There are two fundamental approaches to increasing the soil's organic matter content: one is by enhancing the supply of organic inputs into the soil, and the other is by limiting the processes that lead to organic matter depletion. The level of organic carbon retained in soil is determined by the balance between incoming carbon—derived from plant residues not removed during harvest and ongoing organic conversions—and carbon losses, primarily resulting from microbial decomposition of organic compounds and the subsequent release of carbon dioxide into the air. Organic inputs that return to the soil—whether directly as plant residues or indirectly through manure comprise a diverse range of organic substances. As a result, organic matter in soils serves not only as a vital carbon source supporting biological and chemical processes but also functions as a reservoir for carbon storage. However, tillage practices can diminish the amount of organic carbon present in the soil, which contributes to soil degradation and may lead to a decline in its overall fertility and productive capacity [14].

Understanding how agricultural practices influence soil characteristics is crucial for ensuring the long-term sustainability of soil resources and maintaining ecosystem integrity. The content of organic compounds (0.34%–1.34%) recorded under various land-use types was significantly lower than the threshold required to meet the needs of most agricultural crops, indicating that the structural stability of the soil may be compromised. Consequently, such soils are at greater risk of low fertility and water erosion [7].

As reported by Shepherd et al., the light fraction of soil organic matter plays a key role in shaping soil structure, and noticeable improvements in structural stability occur when fresh organic residues are consistently incorporated into the soil. Therefore, the enhancement of soil's physical condition depends less on the specific farming system employed and more on the volume and quality of organic inputs returned to the soil [25].

Leah T. [13] notes that various locally available organic by-products such as farmyard manure, sewage sludge, wine production residues, distillery effluents, cereal stubble, fermented straw, and similar materials can be effectively utilised to restore and replenish soil organic matter. The use of organic wastes in agricultural practice as fertilisers contributes to maintaining a balanced cycle of carbon and nutrients. Each tonne of organic waste applied as fertiliser replenishes soil humus reserves by 85–100 kg/ha, supplies 8–9 kg/ha of nitrogen, stimulates the increase of productive potential, and improves soil fertility.

The application of fertilizers is a common practice aimed at sustaining or improving crop yields. Over extended periods, consistent fertilization not only boosts crop production but also promotes the accumulation of organic matter in the soil, resulting in enhanced biological activity relative to soils left without fertilization. Long-term fertilizer application has, in many cases, resulted in increased water-stable aggregation, porosity, infiltration capacity, and hydraulic conductivity, as well as reduced bulk density. Fertilizer addition may

also exert physico-chemical effects that influence soil aggregation [10, 21].

Returning straw to the soil is the primary method of managing agricultural crop residues. However, the commonly used practice of straw return often has numerous negative effects on soil fertility levels and the improvement of crop yields [11].

The increased input and improved quality of organic matter entering the soil through the application of winter wheat straw, both alone and in combination with green manure, created more favourable conditions for the development of soil microflora and significantly improved the biological status of the studied soil. According to the findings [24], the application of nitrogen-based fertilizers did not produce any statistically significant changes in the biological characteristics of the studied soils.

As reported by M. Caraman et al. [4], the use of organic fertilizers led to significant improvements in the microbiological and biochemical status of the soil, including a tenfold rise in populations of beneficial microorganisms, an increase in organic matter content ranging from 48.02% to 114.81%, and a rise in humus levels between 10.56% and 15.14%. These changes contributed to enhanced physiological development of plants by 7.69%–10.53%, as well as increases in maize grain yield by 5.98%–17.45% and straw production in comparison with the control treatment.

Long-term application of mineral fertilisers (NPK) without the addition of organic matter may accelerate humus mineralisation and lead to soil quality deterioration, with a range of negative consequences such as nitrogen leaching, increased availability of toxic elements to plants, and reduced energy supply for soil microorganisms. The use of organic fertilisers (such as manure and cattle dung) supports long-term stable crop yields while maintaining optimal soil quality through sustainable long-term management involving surface-active substances. Principal component analysis is a useful tool for assessing changes in soil quality [15].

In China, combining organic amendments with fertilizers led to a substantial increase in the yields of three principal crops wheat, corn, and rice by an average of 29% compared to using organic amendments alone, and by 8% relative to fertilizers applied without organics. Higher nutrient management gains in crop yield under the combined application were observed in the order: wheat (53%) > corn (40%) > rice (8%). Significant and positive temporal trends in nutrient management with organics + fertilisers in wheat and corn yield suggest enhanced resilience of cropping systems. The addition of organic matter, either alone or in combination with fertilisers, improved both the organic matter content and nutrient management compared to the sole application of fertilisers. Despite differences in crop type or land use, the combined use of organics and fertilisers proved to be the most effective approach for increasing food production, enhancing soil organic matter, and improving the sustainability of agroecosystems [31].

In the Left-Bank Forest-Steppe of Ukraine, the continuous application of straw as fertiliser (with a compensatory nitrogen dose) along with mineral fertilisers over a 10-year crop rotation led to an increase in humus content in the arable layer of typical medium loam chernozem by 0.23–0.25%, and humus reserves by 8 t/ha [26]. The application of 40 t/ha of manure + N₁₁₀P₉₀K₉₀ and 20 t/ha of manure + 4 t/ha of straw + N₄₀+ N₁₁₀P₉₀K₉₀ increased the humus content by 25% and 20% respectively, compared to unfertilised plots. The combined incorporation of straw and green manure proved to be an effective measure for restoring soil humus content [1]. Studies conducted by M. Tkachenko et al. in a winter wheat agrocenoses revealed that shallow tillage using a disc harrow combined with resource-saving minimised mineral fertilisation increased the humus content by 0.04% in the 0–15 cm soil layer and by 0.03% in the 15–30 cm layer compared to inversion tillage. High levels of hydrolytic acidity (1.61–2.92 mol/m³/100 g of soil) were observed at all mineral fertiliser rates under inversion tillage [28].

When mineral fertilisers were applied alone at a rate of $N_{46}P_{51}K_{59}$ within a ten-field grain-row crop rotation under adequate moisture conditions, humus losses of 0.09% and 0.03% were observed in the arable and subarable horizons of typical leached chernozem soils, respectively. However, applying 12 t/ha of manure in combination with $N_{46}P_{51}K_{59}$ helped stabilise these humus levels [29].

After completing four crop rotation cycles (40 years) in typical low-humus chernozem soils, the humus content in the arable layer was 4.59% under the treatment with 8.3 t/ha of manure combined with $N_{29.3}P_{45}K_{36.7}$, and 4.72% when 16.7 t/ha of manure was applied alongside the same mineral fertiliser rates. In contrast, fallow plots showed a higher humus content of 5.20%. Additionally, acidification of the soil solution was recorded [31].

At the Poltava State Agricultural Research Station (Ukraine), on typical low-humus heavy loam chernozem, long-term field experiments (1993–2015) demonstrated enhanced soil humus restoration in crop rotations with the annual application of 10 t/ha of manure + $N_{53}P_{60}K_{60}$, combined with the use of all crop residues as organic fertiliser, alongside the obligatory application of a compensatory dose of mineral nitrogen (10 kg of active nitrogen per tonne of straw or stalks) [33].

It has been established that for simple and enhanced restoration of soil humus in typical low-humus chernozem, the annual manure application rate should be 10–15 t/ha, respectively. When manure is partially replaced by crop residues, the annual manure application rate is reduced to 10–12 t/ha. At a manure rate of 6–7 t/ha, an increasing trend in humus balance and high accumulation rates were observed. However, when manure is replaced by crop residues, the rate of humus deficit growth accelerates significantly [6].

The aim of the study was to determine the effectiveness of using crop by-products and green manure for the restoration of humus content in the soil.

MATERIALS AND METHODS

The study was conducted in a five-field crop rotation system during 2020–2024 on the

experimental field of Bila Tserkva National Agrarian University. The soil type was deep typical chernozem with low humus content and medium loam texture. The experiment included four fertilisation systems: 0 – no fertilisers (control); 1 – 8 t/ha of manure + $N_{76}P_{64}K_{57}$; 2 – 12 t/ha of manure + $N_{95}P_{82}K_{72}$; 3 – 16 t/ha of manure + $N_{112}P_{100}K_{86}$. In the first crop rotation variant, all crop residues were removed from the fields. In the second variant, residues were removed only from fields where winter wheat and spring barley were grown; after their harvest, white mustard was sown as a green manure (cover crop). The crop rotation included soybean, winter wheat, sunflower, spring barley and grain maize.

The experiment was conducted in three replications, arranged systematically, continuously, and sequentially across the crop rotation fields. Each sown plot covered an area of 684 m², of which 504 m² was designated for measurement purposes. The mineral fertilisers applied included ammonium nitrate, potassium salt and single superphosphate.

In calculating the humus balance, it was assumed that 60% of the nitrogen removed with the main and by-products of the crop yield originated from soil humus (the remaining share was attributed to nitrogen from organic and mineral fertilisers, as well as atmospheric deposition, plant residues and biological nitrogen fixation). The nitrogen use efficiency from soil sources by plants was estimated at 70%. When determining the amount of humus mineralised, the nitrogen content in humus was assumed to be 5%.

For the calculation of humus mineralization, specific coefficients were applied: 0.8 for typical chernozem soils, 1.8 for row crops, 1.0 for post-harvest white mustard, and 1.2 for other cultivated plants. Additionally, symbiotic nitrogen fixation by nodule bacteria was estimated to account for 50% of the total nitrogen removed through the main and by-products of soybean harvest.

Root residues were estimated according to Yeshchenko [32], while the humus balance was calculated based on the method proposed by Chesnyak [5]. The humification coefficients of plant residues were as follows:

0.23 for soybean, 0.22 for spring barley, 0.20 for winter wheat and corn, 0.15 for white mustard, 0.054 for manure, and 0.20 for the by-products of row crops and soybean.

RESULTS AND DISCUSSIONS

With increasing levels of fertiliser application, both crop yield and the mass of plant residues increased. However, the rate of increase in main yield exceeded that of root biomass and post-harvest residues. In particular, compared with unfertilised plots, the application of the first, second and third fertilisation systems resulted in an increase in main yield of: 93%, 173% and 254% in soybean, while the increase

in root biomass was 65%, 112% and 170%; 82%, 142% and 200% in winter wheat, with corresponding increases in root mass of 56%, 91% and 132%; 50%, 76% and 91% in white mustard (preceded by winter wheat), with 36%, 55% and 62% in root biomass; 77%, 155% and 216% in sunflower, and 57%, 110% and 161% in roots; 62%, 107% and 146% in spring barley, and 40%, 69% and 94% in root biomass; and 66%, 107% and 150% in corn (first crop rotation variant), with 37%, 61% and 93% in root mass, respectively.

Thus, for all studied crops, the increase in main yield was significantly higher than the increase in the dry mass of root residues.

Table 1. Yield of main and by-products and dry weight of root and post-harvest residues in the first variant of crop rotation

Crops	System fertilization	Yield, t/ha		Dry weight, t/ha	
		main products	by-products	root residues	post-harvest residues
Soybean	0	0.92	1.28	0.81	0.54
	1	1.78	2.60	1.34	0.75
	2	2.51	3.87	1.72	1.09
	3	3.26	5.22	2.19	1.48
Winter wheat	0	2.39	2.94	2.57	1.92
	1	4.34	5.43	4.02	2.66
	2	5.79	7.47	4.90	3.08
	3	7.17	9.61	5.96	3.47
Post-harvest white mustard for green manure	0	11.50	–	2.22	0.60
	1	17.22	–	3.01	0.78
	2	20.25	–	3.45	0.89
	3	21.93	–	3.60	0.93
Sunflower	0	1.03	1.61	1.57	0.75
	1	1.82	3.00	2.46	1.01
	2	2.63	4.55	3.30	1.32
	3	3.25	5.75	4.09	1.54
Spring barley	0	2.09	2.32	1.77	1.05
	1	3.38	3.89	2.47	1.34
	2	4.33	5.15	3.00	1.61
	3	5.14	6.37	3.44	1.82
Post-harvest white mustard for green manure	0	10.46	–	2.02	0.55
	1	14.44	–	2.50	0.66
	2	16.82	–	2.85	0.75
	3	18.30	–	3.02	0.79
Corn	0	4.31	6.47	3.61	0.99
	1	7.17	11.11	4.96	1.41
	2	8.93	14.11	5.80	1.73
	3	10.79	17.37	6.98	2.08

Source: Authors own results.

Specifically, under the first, second and third fertilisation systems, the increase in the main part of the yield in soybean exceeded the

increase in root biomass by 28%, 61% and 84%; in winter wheat – by 26%, 51% and 68%; in white mustard – by 14%, 21% and 29%; in

sunflower – by 20%, 45% and 55%; in spring barley – by 22%, 38% and 52%; and in corn – by 29%, 56% and 57% (Tables 1 and 2).

A similar pattern was observed in the second crop rotation variant. This trend was evident in both root and post-harvest residues. Under the first, second and third fertilisation systems, the increase in residue mass, compared to the control, lagged behind the increase in main yield by: 51%, 64% and 79% in soybean; 41%, 78% and 113% in winter wheat; 12%, 20% and 25% in white mustard; 41%, 76% and 105% in sunflower; 28%, 43% and 57% in spring barley; and 24%, 34% and 46% in corn.

In the first crop rotation variant, an average of 4.48 t/ha of dry root mass and 1.88 t/ha of post-

harvest residues were returned annually to the soil. In the second variant, these figures were higher by 11.2% and 10.6%, respectively, amounting to 4.98 and 2.08 t/ha. The total input of organic matter from plant residues to the soil was 6.36 t/ha in the first variant and 7.06 t/ha in the second.

In both the first and second crop rotation variants, the highest amount of plant residues remained after the harvest of winter wheat – 7.15 and 7.79 t/ha, respectively, while the lowest was recorded after soybean – 2.48 and 2.83 t/ha. Under sunflower and spring barley, the amount of residues was nearly the same, amounting to 4.01 and 4.54 t/ha, and 4.13 and 4.55 t/ha, respectively.

Table 2. Yield of main and by-products and dry weight of root and post-harvest residues in the second variant of crop rotation

Crops	System fertilization	Yield, t/ha		Dry weight, t/ha	
		main products	by-products	root residues	post-harvest residues
Soybean	0	1.12	1.52	0.93	0.62
	1	2.11	3.00	1.55	0.85
	2	2.96	4.44	1.98	1.24
	3	3.81	5.94	2.52	1.62
Winter wheat	0	2.73	3.28	2.89	2.15
	1	4.78	5.80	4.39	2.88
	2	6.35	7.87	5.33	3.34
	3	7.80	9.83	6.45	3.73
Post-harvest white mustard for green manure	0	12.43	–	2.41	0.61
	1	18.40	–	3.22	0.83
	2	21.63	–	3.69	0.94
	3	23.49	–	3.88	1.00
Sunflower	0	1.21	1.86	1.79	0.88
	1	2.09	3.39	2.78	1.16
	2	2.98	5.01	3.70	1.50
	3	3.69	6.38	4.59	1.76
Spring barley	0	2.37	2.52	1.96	1.15
	1	3.74	4.06	2.69	1.49
	2	4.78	5.28	3.25	1.83
	3	5.67	6.40	3.75	2.09
Post-harvest white mustard for green manure	0	11.50	–	2.21	0.58
	1	15.64	–	3.00	0.79
	2	18.17	–	3.44	0.93
	3	19.78	–	3.77	1.02
Corn	0	4.82	7.04	4.03	1.09
	1	7.90	11.85	5.50	1.53
	2	9.73	14.89	6.34	1.83
	3	11.74	18.31	7.59	2.16

Source: Authors own results.

With increasing fertiliser application rates, both yield and root residue mass of crops in crop rotations increased. At the same time,

soybean, winter wheat, sunflower and spring barley exhibited a more intensive increase in main yield compared to root biomass. Thus,

under the first, second and third fertilisation systems in the second crop rotation variant, the increase in main yield of soybean, compared to the unfertilised plots, amounted to 88%, 164% and 240%, while the increase in root residues was 67%, 113% and 171%, respectively. In winter wheat, these values were 75%, 133% and 186% for main yield, and 52%, 84% and 113% for root residues. In spring barley – 58%, 102% and 139%, and 37%, 66% and 91%, respectively; in sunflower – 73%, 146% and 205%, and 55%, 107% and 156%.

Thus, under the first, second and third fertilisation systems, the increase in main yield exceeded the increase in root residue mass in soybean by 22%, 51% and 69%; in winter wheat – by 23%, 48% and 63%; in spring barley – by 21%, 36% and 48%; and in sunflower – by 17%, 40% and 47%, respectively. In corn and white mustard under the second crop rotation variant, such a pattern was not observed, and the increases in grain or green biomass and root residues did not differ significantly.

In the second crop rotation variant, the increase in post-harvest residues lagged behind the increase in main yield for all crops grown on fertilised plots, compared to unfertilised ones. It was observed that this discrepancy in growth widened with higher fertiliser rates across all crops, except for soybean. Specifically, under the first, second and third fertilisation systems, the increase in main yield in soybean exceeded the increase in post-harvest residues by 51%, 64% and 58%, respectively; in winter wheat – by 41%, 77% and 112%; in sunflower – by 38%, 72% and 99%; in spring barley – by 28%, 43% and 58%; and in corn – by 5%, 11% and 15%.

Compared with unfertilised plots, the mass of post-harvest residues increased under the first, second and third fertilisation systems by 37%, 100% and 182% in soybean; 34%, 55% and 74% in winter wheat; 35%, 75% and 106% in sunflower; 30%, 59% and 82% in spring barley; and 59%, 91% and 128% in corn.

The average dry mass of root residues in the first and second crop rotation variants

amounted to 1.52 and 1.75 t/ha in soybean, 4.36 and 4.77 t/ha in winter wheat, 2.86 and 3.22 t/ha in sunflower, 2.67 and 2.91 t/ha in spring barley, and 5.34 and 5.87 t/ha in corn. The share of root residues in the total plant residue mass was 60–65% in soybean; 70–72% in winter wheat and spring barley; and 77–79% in sunflower and corn.

On unfertilised plots, the dry mass of root residues per hectare of arable land under the first, second and third fertilisation systems amounted to 2.91, 4.15, 5.00 and 5.86 t in the first crop rotation variant, and 3.24, 4.63, 5.55 and 6.51 t in the second variant. The total plant residue mass was 4.19, 5.87, 7.09 and 8.28 t for the first variant, and 4.66, 6.54, 7.87 and 9.19 t for the second variant. Under the first, second and third fertilisation systems, the increase in plant residue mass in the second crop rotation variant was 40.3%, 68.9% and 97.2%, while the increase in arable land productivity (dry matter basis) was 68.4%, 118.9% and 167.0%, compared to unfertilised variants. Thus, the lag in residue mass increase relative to the productivity growth of the crop rotation intensified with higher fertiliser rates. With increasing fertiliser rates, the ratio of main to by-product yield of crops in the rotation increased. For example, in the second crop rotation variant, under zero, first, second and third fertilisation systems, this ratio was as follows: in soybean – 1.36, 1.42, 1.50 and 1.56; in winter wheat – 1.20, 1.21, 1.24 and 1.26; in sunflower – 1.54, 1.62, 1.68 and 1.73; in spring barley – 1.07, 1.09, 1.11 and 1.13; and in corn – 1.46, 1.50, 1.53 and 1.56. It is quite difficult to determine changes in soil organic matter stocks that are associated with management practices against the background of spatial and temporal variability. In most cases, verifying these changes requires soil sampling over an extended period of time. As an alternative, potential changes in soil organic matter stocks can be assessed using humus balance models, which help to identify the need for humus reproduction in the soil [12].

Table 3. Humus balance in the arable layer (0-30 cm) of soil (in the numerator - the first variant of crop rotation, in the denominator - the second), kg/ha

Crops	System fertilization	Loss of humus					Humus was formed				Humus balance
		Nitrogen removal by the harvest	Nitrogen removal depending on crop and soil composition	Nitrogen removal through humus mineralization	Total consumption of mineralized	Mass of mineralized humus	From plant residues	From by-products in the second variant of crop rotation	From the green mass of white mustard	Total	
Soybean	0	65.3/ 79.5	31.3/ 38.2	15.7/ 19.1	22.4/ 27.3	448/ 546	311/ 357	304		311/ 661	-137/ +115
	1	126.4/ 149.8	60.7/ 71.9	30.3/ 36.0	43.3/ 51.4	867/ 1,028	481/ 552	600		481/ 1,152	-386/ +124
	2	178.2/ 210.2	85.5/ 100.9	42.8/ 50.5	61.1/ 72.1	1,222/ 1,443	646/ 741	888		646/ 1,629	-576/ +186
	3	231.5/ 270.5	111.1/ 129.8	55.6/ 64.9	79.4/ 92.7	1,587/ 1,854	844/ 952	1,188		844/ 2,140	-743/ +286
Winter wheat	0	83.7/ 95.6	80.4/ 91.8	40.2/ 45.9	57.4/ 65.6	1,148/ 1,311	898/ 1,008			898/ 1,008	-250/ -303
	1	151.9/ 167.3	145.8/ 160.6	72.9/ 80.3	104.2/ 114.7	2,083/ 2,294	1,336/ 1,454			1,336/ 1,454	-747/ -840
	2	202.7/ 222.3	194.6/ 213.4	97.3/ 106.7	139.0/ 152.4	2,780/ 3,049	1,596/ 1,734			1,596/ 1,734	-1,184/ -1,315
	3	251.0/ 273.0	241.0/ 262.1	120.5/ 131.1	172.1/ 187.3	3,442/ 3,746	1,886/ 2,036			1,886/ 2,036	-1,556/ -1,710
Post-harvest white mustard for green manure	0	32.2/ 34.8	25.8/ 27.8	12.9/ 13.9	18.4/ 19.9	368/ 397	423/ 453		345/ 373	768/ 826	+400/ +429
	1	48.2/ 51.5	38.6/ 41.2	19.3/ 20.6	27.5/ 29.4	551/ 589	569/ 608		517/ 552	1,086/ 1,160	+535/ +571
	2	56.7/ 60.6	45.4/ 48.5	22.7/ 24.3	32.4/ 34.7	648/ 694	651/ 695		608/ 649	1,259/ 1,344	+611/ +650
	3	61.4/ 65.8	49.1/ 52.6	24.6/ 26.3	35.1/ 37.6	702/ 751	680/ 732		658/ 705	1,338/ 1,437	+636/ +686
Sunflower	0	61.8/ 71.1	89.0/ 102.4	44.5/ 51.2	63.6/ 73.1	1,271/ 1,462	325/ 374	372		325/ 746	-946/ -716
	1	109.2/ 123.9	157.2/ 178.4	78.6/ 89.2	112.3/ 127.4	2,246/ 2,548	486/ 552	678		1,566/ 2,310	-680/ 238
	2	157.8/ 177.3	227.2/ 255.3	113.6/ 127.7	162.3/ 182.4	3,246/ 3,648	647/ 728	1,002		2,267/ 3,350	-979/ -298
	3	195.0/ 219.9	280.8/ 316.7	140.4/ 158.4	200.6/ 226.3	4,011/ 4,526	788/ 889	1,276		2,948/ 4,325	-1,063/ -201
Spring barley	0	52.3/ 60.8	50.2/ 58.4	25.1/ 29.2	35.9/ 41.7	717/ 834	620/ 684			620/ 684	-97/ -150
	1	84.5/ 95.0	81.1/ 91.2	40.6/ 45.6	57.9/ 65.1	1,159/ 1,302	838/ 920			838/ 920	-321/ -382
	2	108.3/ 121.0	104.0/ 116.2	52.0/ 58.1	74.3/ 83.0	1,485/ 1,660	1,014/ 1,118			1,014/ 1,118	-471/ -542
	3	128.5/ 143.3	123.4/ 137.6	61.7/ 68.8	88.1/ 98.3	1,762/ 1,966	1,157/ 1,285			1,157/ 1,285	-605/ -681
Post-harvest white mustard for green manure	0	29.3/ 32.2	23.4/ 25.8	11.7/ 12.9	16.7/ 18.4	335/ 368	386/ 419		314/ 345	700/ 764	+365/ +396
	1	40.4/ 43.8	32.3/ 35.0	16.2/ 17.5	23.1/ 25.0	462/ 500	467/ 569		433/ 469	900/ 1,038	+438/ +538
	2	47.1/ 51.7	37.7/ 41.4	18.8/ 20.7	26.9/ 29.6	538/ 591	540/ 656		505/ 545	1,045/ 1,201	+507/ +610
	3	51.2/ 55.4	41.0/ 44.3	20.5/ 22.2	29.3/ 31.7	585/ 634	572/ 719		549/ 593	1,121/ 1,312	+536/ +678
Corn	0	146.5/ 163.9	211.0/ 236.0	105.5/ 118.0	150.7/ 168.6	3,014/ 3,371	920/ 1,024	1,408		920/ 2,432	-2,094/ -939
	1	243.8/ 268.6	351.1/ 386.8	175.5/ 193.4	250.8/ 276.3	5,015/ 5,525	1,174/ 1,406	2,370		2,254/ 4,856	-2,761/ -669
	2	303.6/ 330.8	437.2/ 476.4	218.6/ 238.2	312.3/ 340.3	6,245/ 6,805	1,418/ 1,634	2,978		3,038/ 6,232	-3,207/ -573
	3	366.9/ 399.2	528.3/ 574.8	264.2/ 287.4	377.4/ 410.6	7,548/ 8,211	1,656/ 1,950	3,662		3,816/ 7,772	-3,732/ -439

Source: Authors own results.

Humus balancing methods are simple tools for assessing the interaction between agricultural land use and soil organic matter. Approaches to humus balancing vary significantly in their specific objectives, scope, and methodological framework. The term "humus balance" encompasses both simple models for the quantitative assessment of changes in soil organic matter or soil organic carbon, and models aimed at optimising soil performance in the arable layer by calculating the need for organic fertilisers without a quantitative estimation of changes in organic matter or organic carbon [2].

When all by-products are removed from the fields, only white mustard demonstrates a positive humus balance; for all other crops in the rotation, the humus balance is negative across all experimental variants. After corn, annual humus losses on unfertilised plots amount to 2 t/ha, whereas under the variant with 40 t/ha of manure plus N₁₅₀P₁₂₀K₁₃₀, losses increase to 3.7 t/ha (Table 3).

Under the first, second and third fertilisation systems, the proportion of humus formed from plant residues was 85.5%, 63.2%, 59.9% and 57.8%, respectively; from manure – 0%, 25.5%, 29.8% and 33.0%; and from green manure biomass – 14.5%, 11.3%, 10.3% and 9.2%.

When by-products of soybean, sunflower and corn are used as organic fertiliser, the overall humus balance in the crop rotation remains negative, amounting to 234 kg/ha under the zero fertilisation system, 179 kg/ha under the first, 256 kg/ha under the second, and 277 kg/ha under the third system. Thus, humus losses when all by-products are removed from the fields are almost four times higher than when part of them is used as organic fertiliser. When wheat and spring barley straw is used as fertiliser, an additional amount of humus would be added to the soil as follows: under the zero fertilisation system, 131 and 111 kg/ha; under the first system, 232 and 179 kg/ha; under the second, 315 and 232 kg/ha; and under the third, 393 and 282 kg/ha, respectively.

The use of by-products from cereal grain crops as organic fertiliser would enrich the soil with

humus by 242, 411, 547 and 675 kg/ha, respectively. Under these conditions, the humus balance on unfertilised plots would be positive (+8 kg/ha), while on fertilised plots it would be profitable, amounting to 232 kg/ha under the first fertilisation system, 291 kg/ha under the second, and 398 kg/ha under the third.

Under the first, second and third fertilisation systems, the proportion of humus formed from crop residues in the rotation was 60.7%, 47.0%, 44.0% and 42.2%, respectively; from manure – 0%, 16.8%, 19.5% and 21.3%; from by-products – 29.3%, 28.3%, 29.3% and 30.2%; and from the green biomass of white mustard – 10.0%, 7.9%, 7.2% and 6.3%.

The data convincingly demonstrate that the dominant source of humus formation is crop residues, whose humification generated 1.66 times more humus than that derived from the by-products of the three crops in the rotation.

If by-products of all crops in the rotation without exception are used as organic fertiliser, the proportion of humus formed from their humification will increase to 44–46%, and on fertilised plots their effectiveness may even slightly exceed that of crop residues.

Under the condition of using cereal straw as organic fertiliser, the soil would receive an additional 242 kg/ha of humus on unfertilised plots, 411 kg/ha under the first fertilisation rate, 547 kg/ha under the second, and 657 kg/ha under the third fertilisation rate.

In ecological farming, it is necessary to maintain an optimal ratio of mineral to organic fertilisers.

This is determined by the index of agricultural ecologisation, which is calculated by dividing the mass (kg/ha) of applied mineral fertilisers (active substance) by the mass (t/ha) of organic fertilisers [30].

Up to 15 kg of active substance of mineral fertilisers should be applied per tonne of organic fertiliser [27].

Under the first, second and third fertilisation systems, the amount of organic fertiliser applied to the soil was 4.39, 14.33, 19.41 and 24.05 t/ha in the first crop rotation variant, and 6.87, 18.46, 24.83 and 30.78 t/ha in the second variant.

The agricultural ecologisation coefficient was 0, 13.7, 12.8 and 12.4 when all by-products of crops were removed from the fields, and 0, 10.7, 10.0 and 9.7 when they were used as organic fertiliser in three fields.

According to the ecologisation index and the rates of applied organic fertilisers, only the plots in the second crop rotation variant receiving the highest fertiliser rate correspond to an intensive level of agricultural ecologisation; the remaining fertilised plots in both variants fall within a transitional level.

CONCLUSIONS

With increasing fertiliser application rates, the dry matter yield of the main crop products in the rotation increases at a faster rate than the mass of plant residues. On average, 6.36 t/ha of dry plant residues are returned annually to the soil when all by-products of crops are removed from the fields, and 7.06 t/ha when only cereal straw is removed.

When all by-products are removed from the fields, the humus balance in the rotation is negative on unfertilised plots and plots fertilised with 8 t/ha manure + N₇₆P₆₄K₅₇, 12 t/ha manure + N₉₅P₈₂K₇₂ and 16 t/ha manure + N₁₁₂P₁₀₀K₈₆, amounting to -551, 785, 1,060 and 1,305 kg/ha, respectively. When all by-products of crops in the rotation are used as organic fertiliser, the soil humus balance is positive at 8, 232, 291 and 398 kg/ha, respectively.

According to the agricultural ecologisation index and rates of organic fertiliser application, the rotation variant where by-products are used as organic fertiliser in three fields and 16 t/ha manure + N₁₁₂P₁₀₀K₈₆ is applied per hectare corresponds to an intensive level of agricultural ecologisation.

The productivity of the rotation with complete removal of all by-products is 11–13% lower than that of the rotation where by-products are used as organic fertiliser in three fields.

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