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Decrease in fertility of typical chernozem due to long-term anthropogenic pressure in grain-beet crop rotations

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Abstract. The saturation of sugar beet rotations under different fertilizer application systems and long-term cultivation induces significant changes in soil properties, leading to decreases in humus content, mineral nitrogen, phosphorus, and potassium. The study was conducted in a stationary multifactorial experiment in grain-beet crop rotations: crop rotation, row-crop, and grain-row crop rotations with the application of 40 t/ha of manure under sugar beets + NPK 100:90:90 and a variant without fertilizers. The paper presents the results of monitoring changes in humus content during each rotation, reduction of humus reserves in the plow layer, and physicochemical and agrochemical soil indicators. In the variants without fertilizers, we observed 0.24–0.41% decline in humus content in all crop rotations during 3 rotations of ten-field crop rotations (30 years). Overall, there occurred 0.89–1.00% decrease over 50 years of anthropogenic influence, equivalent to 31.8–35.7 t/ha, or 23.1–26.1% of initial reserves per hectare. Despite application of 40 t/ha of manure + NPK 100:90:90 under sugar beets, humus loss was 27.5 t/ha in the row-crop rotation and 16.8 t/ha in the grain-row crop rotation. Fertilizer application led to increase in exchangeable and hydrolytic soil acidity. With the application of 6.7 t/ha of manure + NPK 53:42:42 per 1 ha of crop rotation area, there was a tendency towards increase in mineral nitrogen content, mobile phosphorus doubled to 280.1–302.8 mg/kg compared to the variant without fertilizers, and exchangeable potassium decreased regardless of the fertilization system, which was associated with its utilization by plants. Sugar-beet yield increased to 44.76 t/ha in the crop-rotation under the organo-mineral-fertilizer application system, exceeding the spring wheat rotation by 4.63 t/ha and the variants without fertilizers by 2.45–2.72 times. Therefore, the modern fertilizer application system under sugar beets did not ensure stabilization of humus content in the soil and increased its acidity. It is necessary to more broadly use cover crops in crop rotations, incorporate crop residues, and apply biological preparations to improve soil fertility.

Keywords: sugar beet; humus content; mineral nitrogen; phosphorus; potassium: yield.

Introduction

In the context of the climate change and uneven distribution of rainfall, saturation of crop rotations with high-margin monocultures, and reduced application of organic fertilizers, soil fertility deterioration are becoming a pressing issue. The problem of nutrient imbalance has intensefied, soil solution acidity is increasing, and humus content is decreasing. To address the nitrogen deficiency issue as the most limiting factor, it is recommended to maximize the saturation of crop rotations with leguminous crops and use organo-mineral fertilizers, crop residues, and straw as sources for stabilizing and increasing soil humus content (Gamayunova et al., 2020; Truskavetskiy et al., 2020; Varga et al., 2022).

The main direction of research at the Institute of Bioenergy Crops and Sugar Beets of the National Academy of Agrarian Sciences of Ukraine, along with its network of research stations, is to study the impact of crop-rotation systems and fertilizer application on formation of soil fertility (Barshtein et al., 2002; Zaryshniak et al, 2012; Tsvey, 2014). Preserving the fertility potential of highly humus-rich typical chernozem soils in short rotation crop systems requires optimizing the fertilizer application system and adjusting their doses depending on the crop's characteristics. It also involves the ability to utilize nutrients in case of soil moisture deficiency.

The main component of the soil complex that indicates soil fertility and directly influences it is humus content. It serves as an indicator of the integrated level of fertility, as well as the physical and physicochemical properties that ensure the optimal flow of soil processes and the adaptability of agricultural plants to form productivity (Markovska et al., 2020). Humus reserves indicate the direction of soil-forming processes, ensuring its water, air, and nutrient regimes. Humus is a source of synthesis of a large number of nutrients for plants, improving the physicochemical properties of the soil and its microbiological community (Körschens et al., 2013; Götze et al., 2016; Martyniuk et al., 2023).

The fertilizer application system should be based on the physiological needs of the plants and the creation of an optimal nutritional regime for the crops and the entire crop rotation, taking into account agrotechnical peculiarities and drier weather conditions. The use of mineral fertilizers in combination with organic ones allows for saturation of the soil with exchangeable forms of nutrients, forming a unique trophic environment as a result of the transformation of the organomineral substrate of fertilizers, which ensures the stability of the organic colloid complex. (Hergert, 2010; Baliuk et al., 2018; Martyniuk, 2020).

The saturation of crop rotations with sugar beets under different fertilizer application and soil tillage systems during long-term systematic interaction causes significant changes in soil properties, resulting in decreases in humus content, mineral nitrogen, phosphorus, and potassium (Hospodarenko et al., 2018, 2019). According to the data from the O. N. Sokolovskyi Institute of Soil Science and Agrochemistry, over 25–30 years, the average humus content in typical chernozem soils in Ukraine has decreased from 3.64% in 1961 to 3.16% in recent years, and this trend continues to decline (Baliuk et al., 2017; Symochko et al., 2024).

The objective of the research was assessing the long-term (50 years) application of organo-mineral fertilizers in grain-beet crop rotations and its impact on changes in the soil fertility indicators (humus, acidity, mineral nitrogen, phosphorus, and potassium). This includes identifying the nature of the interaction between crop rotation systems and fertilization methods on crop yield formation.

Materials and methods

The long-term studies of this issue were conducted in the Right-Bank Forest Steppe of Ukraine at the Bila Tserkva Research and Breeding Station in a stationary experiment on typical deep chernozem soils with the humus content in the 0–30 cm layer ranging 3.0% to 3.8%, and the mobile forms of phosphorus and potassium (according to Chirikov) ranging 153 to 170 mg/kg and 64 to 78 mg/kg, respectively. The main climatic characteristics of the research area included an average annual precipitation of 526 mm, which can vary from 350 to 750 mm in individual years. The amount of precipitation that falls during periods with temperatures above 10 °C is approximately 306 mm, with uneven distribution throughout the year: the highest amount falls during the warm months, while the lowest falls during the winter period. The air temperature has been increasing annually, especially during winter and summer months. For several years now, there have been abnormally warm winters, with air temperatures in January and February exceeding the long-term average by +5–7 °C.

The long-term multifactorial experiment was established in 1973–1976 at the Bila Tserkva Research and Breeding Station in the Right-Bank Forest Steppe of Ukraine. It comprised 10-field crop rotations over the following periods: rotation I (1973–1983), rotation II (1984–1994), and rotation III (1995–2005). The crop rotations were as follows: crop rotation: 1) clover; 2) winter wheat; 3) sugar beet; 4) pea; 5) winter wheat; 6) sugar beet; 7) corn; 8) winter wheat; 9) sugar beet; 10) barley with grass underseeing (30% row crop, 50% cereals, 20% fodder crops). Row-crop rotation: 1) corn; 2) winter wheat; 3) sugar beet; 4) corn; 5) winter wheat; 6) sugar beet; 7) corn; 8) winter wheat; 9) sugar beet; 10) barley (50% row crop, 40% cereals, 10% fodder crops). Grain-row crop rotation: 1) pea; 2) winter wheat; 3) sugar beet; 4) pea; 5) winter wheat; 6) winter wheat; 7) corn; 8) winter wheat; 9) sugar beet; 10) barley (20% row crop, 70% cereals, 10% fodder crops).

In rotation III from 1995 to 2005, the first crop was replaced with oilseed radish for green mass, while other crop rotations and crops remained unchanged. Starting from 2006, the options for soil fertility restoration were implemented, increasing the number of organic fertilizers for sugar beets to 50 t/ha of manure + NPK 100:100:100. The crop rotations were reformed into six-field rotations. The first rotation of six-field crop rotations from 2007 to 2012, with alternation in the crop rotation, included: 1) oats and vetch cover crop; 2) winter wheat; 3) sugar beet; 4) barley + clover; 5) clover; 6) winter wheat (17% row crop, 50% cereals, 33% fodder crops). The row-crop rotation was as follows: 1) oats and vetch cover crop; 2) winter wheat; 3) sugar beet; 4) barley; 5) corn; 6) corn (50% row crop, 33% cereals, 17% fodder crops). The grain-row crop rotation included: 1) oats and vetch cover crop; 2) winter wheat; 3) sugar beet; 4) barley; 5) rapeseed; 6) winter wheat (33% row crop, 50% cereals, 17% fodder crops). In rotation from 2013 to 2018, soybeans and sunflowers were added instead of the 5th and 6th corn crops in the row-crop rotation. Since 2019, in the third rotation, spring oats were added instead of winter rapeseed in the grain-row crop rotation. For 1 ha of crop-rotation area, NPK 50:66:66 + organic fertilizers were applied in rotations I end II, 6 t/ha of manure in rotation III. Starting from 2006, 9 t/ha of manure + NPK 43:43:43 were applied, and from 2019, 6.7 t/ha of manure + NPK 53:42:42 per 1 ha of crop-rotation area. The fertilization system for each crop is provided in the tables.

The methods of soil sample analysis have remained consistent since the start of the stationary experiment: NO_3^-–N^+ (DSTU ISO 14255:2005 Soil quality. Measurements of nitrate nitrogen, ammonium nitrogen, and total soluble nitrogen in air-dry soils were carried out using calcium chloride solution for extraction), NH_4^+–N by the colorimetric method, mobile phosphorus and potassium by the Chirikov's method (DSTU 4115:2004. Soils. Identification of mobile compounds of phosphorus and potassium by the modified Chirikov's method), humus by the Tyurin's method (DSTU 4289:2004. Soil quality. Methods of measuring organic matter), hydrolytic acidity (DSTU 7537:2014. Soil quality. Measurement of hydrolytic acidity), soil pH, sum of absorbed bases (DSTU ISO 11260-2001). Soil-fertility indicators were identified in the sugar beet fields in two periods: the stage of 2–3 true leaf pairs and during harvesting. Soil samples for humus content were taken in the 0–30 cm soil layer after harvesting sugar beet. Humus reserves were estimated in the 0–30 cm soil layer considering the average soil density of 1.19 g/cm^3.

Crop cultivation techniques were as follows: tillage with plowing to the depth of 28–30 cm for sugar beets, 20–22 cm for winter wheat and corn, and shallow disc harrowing to the depth of 12–15 cm for other crops. The used varieties were: winter wheat – Ros, barley – Komandor, sugar beets – Zluka. Fertilizers were applied to all crops in the rotation except for oats and barley. For sugar beets, 300 kg/ha of ammonium nitrate (N 34), 320 kg/ha of granulated superphosphate (P 28), and 140 kg/ha of potassium chloride (K 62) were applied by broadcast spreading. For winter wheat, the rates were 260, 210, and 140 kg/ha respectively; for clover, soybeans, and spring oats – 250 kg/ha of nitroamofoska (NPK 16:16:16). Semi-rotted manure was applied at the rate of 20 t/ha for the first and second rotations under sugar beets and 30 tons for the third rotation, increased to 50 t/ha since 2006, and 40 t/ha since 2019. Yield assessment was conducted on test plots with the area of 100 m^2 in three replicates, with subsequent conversion to tons per hectare. Side products such as beet pulp – according to forty samples of root crops, and straw – by a test bundle.

All the groups were compared using one-way analysis of variance (ANOVA) with the Bonferroni's Correction, mean ± standard deviation (x ± SD). Tukey post hoc test was used for multiple comparisons.

Results

The research findings indicate that the long-term anthropogenic pressure led to decrease in the soil humus content. Regardless of crop rotation sequences, by the end of rotation I, in the variants without fertilizers, its content decreased by 0.09–0.27%, by the end of the second rotation – by 0.38–0.48%, and by the end of the third rotation – by 0.58–0.79%, compared to the beginning of the experiment, 3.83–3.86% (Table 1). Despite the application of fertilizers at the rate of 6 t/ha of manure + NPK 50:66:66 per 1 ha of crop rotation area, humus content decreased during two rotations in the row-crop rotation by 0.16%, in the crop rotation by 0.05%, and remained at the same level in the grain-row crop rotation. By the end of rotation III of ten-field crop rotations, 0.24–0.41% decrease in humus content was observed in all crop rotation sequences, compared to the beginning of the experiment.

With the transition to six-field crop rotations from 2006, in the variants without fertilizers, the humus content continued to decrease throughout the subsequent rotations to 2.97%, 2.83%, and 2.94% in all the crop rotations. Starting from the first and second rotations of six-field crop rotations, the manure dose under sugar beets was increased to 50 t/ha, and overall, 9 t/ha of manure + NPK 43:43:43 was applied to 1 ha of crop rotation area, which helped stabilize the decrease in humus. In rotations I and II of six-field crop rotations, the humus content decreased by 0.10% in the row-crop rotation, while in other rotations, it decreased only by 0.02–0.03% compared to the previous rotation. From 2013 to 2018, we observed a slight, 0.26% increase in the humus content compared to rotation I in the crop rotation, no change in the row-crop rotation, and 0.06% decrease in the grain-row crop rotation. Since 2019, considering economic feasibility and shortage of organic fertilizers, the manure dose under sugar beet was reduced to 40 t/ha, and to 1 ha of crop rotation area, 6.7 t/ha of manure + NPK 53:43:43 was applied. As a result, we observed 0.13–0.15% decrease in the humus content in the crop rotations compared to the previous rotation (2013–2018), and 0.30% decrease in the row-crop rotation. Thus, despite the organ mineral fertilization system over 50 years, as of 2022, the humus content decreased the most in the row-crop rotation, by 0.77% (from 3.81% to 3.04%).

The loss of humus in the 0–30 cm soil layer in the variant without fertilizers at the end of rotation I amounted to 3.2 t/ha in the crop rotation, 5.3 t/ha in the row-crop rotation, and 9.7 t/ha in the grain-row crop rotation. By the end of rotation III in 2004–2005, these losses increased to 13.6, 17.1, and 15.7 t/ha, respectively. With the transition to six-field crop rotations from 2007 to 2018, the losses of humus in the variants without fertilizers remained at different levels, which was associated with decrease in sugar beet saturation from 2–3 fields in the ten-field crop rotation to field 1 (17.0% saturation), the introduction of forage crops into the crop rotation (fallow-oats), and increase in the amount of plant root residues. However, the humus reserves as of 2021–2022 decreased by 6.1 and 7.1 t/ha in the crop rotation and grain-row crop rotation, respectively, and by 9.7 t/ha in the row-crop rotation. This is associated with the introduction of soybeans and sunflowers into the row-crop rotation and a general decrease in soil fertility.

Table 1
Changes in humus content (%) of typical chernozem depending on fertilizer application and crop rotation sequences in the Right-Bank Forest-Steppe of Ukraine, soil layer 0–30 cm (n = 3, x ± SD)

Crop rotation	Fertilization system	At the beginning of the experiment	Ten-field crop rotations			Six-field crop rotations		
			I rotation 1973–1983	II rotation 1984–1994	III rotation 1995–2005	I rotation 2007–2012	II rotation 2013–2018	III rotation 2019–2022
Crop rotation	without fertilizers	3.86 ± 0.07^{d}	3.77 ± 0.11^{d}	3.48 ± 0.14^{c}	3.07 ± 0.04^{a}	3.11 ± 0.05^{ab}	3.14 ± 0.06^{b}	2.97 ± 0.10^{a}
	organomineral fertilization system	3.86 ± 0.05^{b}	3.85 ± 0.08^{b}	3.81 ± 0.08^{b}	3.32 ± 0.20^{a}	3.29 ± 0.13^{a}	3.55 ± 0.18^{a}	3.42 ± 0.11^{a}
Row-crop	without fertilizers	3.83 ± 0.14^{d}	3.68 ± 0.10^{d}	3.35 ± 0.11^{c}	3.13 ± 0.07^{b}	3.14 ± 0.06^{b}	3.10 ± 0.17^{ab}	2.83 ± 0.13^{a}
	organomineral fertilization system	3.81 ± 0.09^{c}	3.74 ± 0.03^{c}	3.65 ± 0.09^{bc}	3.44 ± 0.15^{b}	3.34 ± 0.08^{b}	3.34 ± 0.18^{b}	3.04 ± 0.08^{a}
Grain-row crop	without fertilizers	3.84 ± 0.10^{d}	3.57 ± 0.13^{cd}	3.40 ± 0.04^{c}	3.26 ± 0.16^{abc}	3.27 ± 0.14^{abc}	3.14 ± 0.05^{a}	2.94 ± 0.15^{a}
	organomineral fertilization system	3.77 ± 0.02^{c}	3.74 ± 0.04^{c}	3.78 ± 0.02^{c}	3.53 ± 0.09^{ab}	3.51 ± 0.20^{a}	3.45 ± 0.16^{a}	3.30 ± 0.09^{a}

Note: groups were compared within rows (between crop rotation cycles) using ANOVA with the Bonferroni's Correction; multiple comparison of data within rows was conducted using the Tukey's Test; fertilization system: for the first and second rotations, 20 t/ha of manure + NPK 80:100:100 was applied under sugar beets, and for 1 ha of crop rotation area, 6 t/ha of manure + NPK 50:66:66 was applied; for the III rotation, the amount of organic matter was increased to 30 t/ha of manure; fertilization system for other crops: pea, winter wheat NPK 40:60:40, corn NPK 100:60:60, barley PK 60:60; in the row-crop rotation, no fertilizers were applied for corn on the 1st field, corn on the 4th field received NPK 40:60:60, similarly in the grain-fallow rotation, peas on the 1st field received no fertilizers, and peas on the 4th field received NPK 40:60:60; for the I, II rotations of six-field crop rotations, 50 t/ha of manure + NPK 100:100:100 were applied under sugar beet, and for 1 ha of crop rotation area, 9 t/ha of manure + NPK 43:43:43 (no fertilizers were applied for barley and oats), winter wheat, corn NPK 60:60:60, rapeseed and clover NPK 40:40:40. In 2019 onwards, 40 t/ha of manure + NPK 100:90:90 were applied under sugar beets, and for 1 ha of crop rotation area, 6.7 t/ha of manure + NPK 53:42:42, winter wheat, sunflower – NPK 90:60:60, clover, soybeans, spring oats – NPK 40:40:40.

With the application of organo-mineral fertilizers at the rate of 6 t/ha of manure + NPK 50:66:66 per 1 ha of crop rotation area and 20 t/ha of manure + NPK 80:100:100 under sugar beets, the humus reserves in the 0–30 cm soil layer tended to decrease. In the crop rotation and row-crop rotation, we observed 1.8 and 5.7 t/ha decreases, respectively, over 2 rotations, while the grain-row crop rotation remained unchanged due to the greater presence of cereal crops and only two fields of sugar beets. By the end of rotation III, despite increase in the fertilizer dose under sugar beets to 30 t/ha, the humus reserves decreased by 20.2 t/ha in the crop rotation, 13.2 t/ha in the row-crop rotation, and 8.6 t/ha in the grain-fallow rotation compared to the beginning of the study. Only with the transition to six-field crop rotations, reducing the saturation of crop rotations with sugar beets from 30% to 17% and the application of 50 t/ha of manure + NPK 100:100:100, and 9 t/ha of manure + NPK 43:43:43 per 1 ha of crop rotation area, it was possible to stabilize the humus reserves over two rotations (2007–2018) in the row-crop rotation at 119.2 t/ha, in the grain-row crop rotation at 123.2–125.3 t/ha, and even increase them in the crop rotation by +9.2 to 126.7 t/ha. As of 2022, with application of 40 t/ha of manure + NPK 100:90:90 under sugar beets and 6.7 t/ha of manure + NPK 53:42:42 per 1 ha of crop rotation area, the humus reserves decreased the most in the row-crop rotation by 11.0 t/ha compared to the previous rotation, while in others, they remained at 4.6–5.4 t/ha level.

In the variants without fertilizers, there was saan a linear regression of humus loss over 50 years with coefficients of determination for the crop rotation $R^2 = 0.8491$, row-crop rotation $R^2 = 0.9173$, and grain-row crop rotation $R^2 = 0.9397$ (Fig. 1).

In the crop rotations with sugar beet crops, application of organo-mineral fertilizers led to increase in soil acidity both at the end of rotation III and in the years 2021–2022, where the soil pH ranged 6.07 to 4.98 units due to leaching of Ca and Mg from the soil-absorbing complex. The same trend was observed in row-crop and grain-row crop rotations with pH levels of 4.85 and 4.86 units, respectively (Table 2). The use of soil without fertilizer application resulted in decrease in exchangeable calcium and magnesium contents, consequently lowering soil pH in all crop rotation stages.

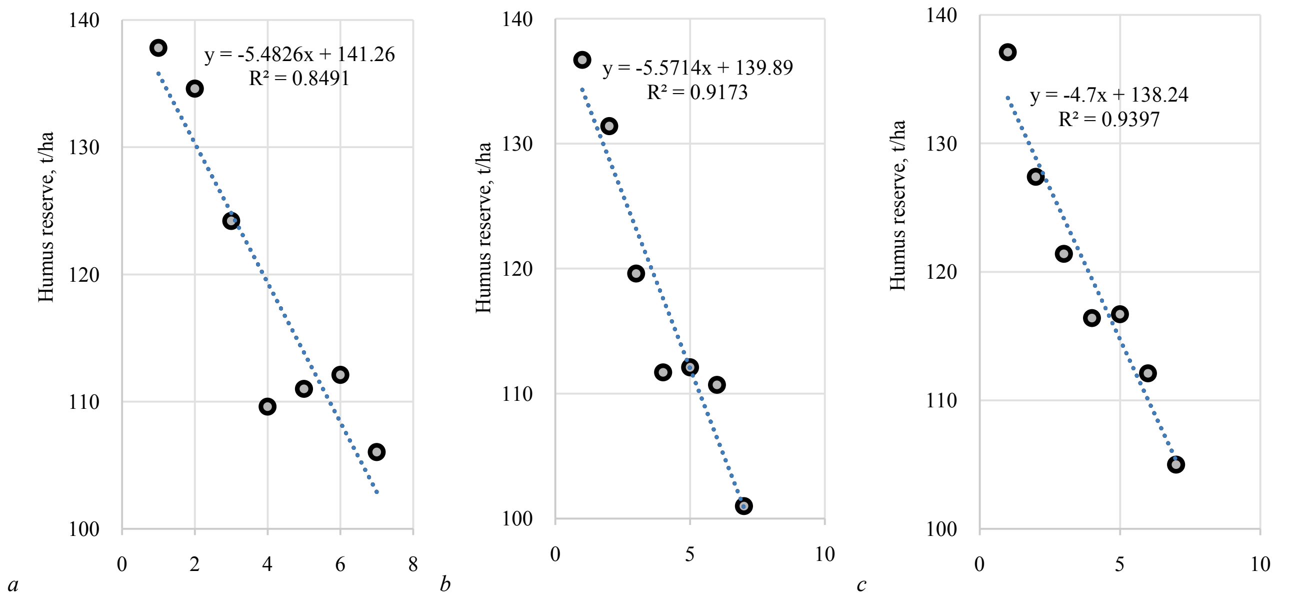

Fig. 1. Linear dependence of humus loss in typical chernozem soil without fertilizer application over 50 years, conducted at the Bilohirsk Experimental Breeding Station of the Right-Bank Forest-Steppe of Ukraine (n = 7): *a* – crop rotation, *b* – row-crop, *c* – grain-row crop rotation

Table 2
Physical and chemical indicators of chernozem depending on the fertilizer application system and crop rotation stages during sugar beet harvesting period in the conditions of the Right-Bank Forest-Steppe of Ukraine (n = 3, x ± SD)

Crop rotation	The system of fertilization for sugar beets	Soil pH		Hydrolytic acidity, mmol/100 g of soil		Sum of exchangeable bases, %	
		2005–2006	2021–2022	2005–2006	2021–2022	2005–2006	2021–2022
Crop rotation	without fertilizers	6.51 ± 0.17^{b}	5.11 ± 0.25^{a}	3.28 ± 0.40^{a}	2.83 ± 0.28^{a}	24.41 ± 0.46^{b}	20.32 ± 0.96^{a}
	40 t/ha of manure + NPK 100:90:90	6.07 ± 0.45^{b}	4.98 ± 0.14^{a}	3.54 ± 0.28^{ab}	3.39 ± 0.36^{a}	24.48 ± 0.47^{b}	20.83 ± 0.37^{a}
Row-crop	without fertilizers	5.78 ± 0.07^{b}	5.17 ± 0.35^{a}	2.80 ± 0.37^{a}	2.74 ± 0.31^{a}	24.80 ± 0.67^{d}	20.71 ± 0.38^{b}
	40 t/ha of manure + NPK 100:90:90	5.84 ± 0.08^{b}	4.85 ± 0.18^{a}	2.70 ± 0.20^{a}	3.99 ± 0.49^{b}	23.72 ± 0.21^{c}	19.80 ± 0.33^{a}
Grain-row crop	without fertilizers	5.62 ± 0.22^{b}	5.16 ± 0.18^{a}	3.20 ± 0.21^{a}	2.90 ± 0.48^{a}	23.24 ± 1.61^{c}	20.38 ± 0.43^{b}
	40 t/ha of manure + NPK 100:90:90	5.20 ± 0.24^{ab}	4.86 ± 0.19^{a}	3.20 ± 0.19^{a}	4.90 ± 0.41^{b}	23.63 ± 0.92^{c}	18.72 ± 0.87^{a}

Note: within each crop rotation, comparisons were made between study years using ANOVA with the Bonferroni's Correction; standard deviations were calculated based on 3 replications; multiple comparisons of data in rows were conducted using the Tukey's Test.

A more precise criterion for evaluating acidity of chernozem soils is hydrolytic acidity, which for sugar beets should not exceed 1.80 mmol/100 g of soil. In the conducted research, in variants with fertilizer application, hydrolytic acidity increased to 3.39, 3.99, and 4.90 mmol/100 g of soil depending on the crop rotation stages, compared to 2005–2006. Meanwhile, in the variants without fertilizer application, hydrolytic acidity remained at the same level compared to the previous period. There was observed a tendency towards decrease in hydrolytic acidity in all crop rotation stages. The sum of absorbable bases decreased in all crop rotation stages both with and without fertilizer application, attributed to the loss of Ca and Mg from the soil-absorbing complex.

The content of available nitrogen in chernozem soils is closely related to the amount of organic matter, moisture level, soil fertility, terrain relief, and depends on the fertilization system and the characteristics of crop rotation stages. For instance, during the sugar beet seedling stage in crop rotations, the content of mineral nitrogen with the application of 40 t/ha of manure + NPK 100:90:90 was 21.7 mg/kg, exceeding the variant without fertilizers by 7.5 mg/kg, or 1.53 times (Table 3). Identical trends were observed in other crop rotations. By the harvesting period, the content of mineral nitrogen decreased 1.72–2.50-fold due to its utilization by plants. In the variants without fertilizers, the amount of mineral nitrogen during the sugar beet seedling stage did not change significantly compared to the 2005–2006 period, and even increased from 11.2 to 14.2 mg/kg in crop rotations, which was associated with microbiological activity and humus mineralization.

During three rotations of six-year crop rotations, the content of available phosphorus during the sugar beet seedling stage remained relatively unchanged (decreased by 22.3 mg/kg in crop rotation, remained unchanged in row-crop rotation, increased by 43.1 mg/kg in grain-row crop rotation), which was attributed to the low utilization coefficient of phosphorus by the crops in the crop rotation, as well as replenishment of phosphorus in the soil through root residues. With the application of 6.7 t/ha of manure + NPK 53:42:42 per hectare of crop rotation area and 40 t/ha of manure + NPK 100:90:90 for sugar beets, the content of available phosphates during the seedling stage ranged 179.6 to 302.8 mg/kg, which was a very high value according to the soil grouping scale. By the harvesting period of sugar beets, the phosphorus content decreased only by 33.6–40.5 mg/kg depending on the crop rotation stages. Considering the high phosphorus content in the soil and additional inputs from fertilizers and straw from grain crops, the application rate of phosphorus fertilizers should be reduced to prevent soil phosphorus saturation. Meanwhile, in the variants without fertilizers, the content of available phosphorus continued to decrease both during the sugar beet seedling stage to 141.8–185.7 mg/kg of soil and during the harvesting period to 104.1–172.1 mg/kg.

Table 3
Agrochemical indicators of typical leached chernozem in sugar beet crops of the Right-Bank Forest-Steppe of Ukraine, mg/kg (n = 3, x ± SD)

Crop rotation	Fertilization system	NO_3^-–N+ NH_4^+–N				P_2O_5				K_20			
		1*		2**		1*		2**		1*		2**	
		2005–2006	2021–2022	2005–2006	2021–2022	2005–2006	2021–2022	2005–2006	2021–2022	2005–2006	2021–2022	2005–2006	2021–2022
Crop rotation	without fertilizers	11.2 ± 2.6^{a}	14.2 ± 0.9^{a}	7.3 ± 0.8^{a}	6.2 ± 0.4^{a}	164.1 ± 5.1^{b}	141.8 ± 11.2^{a}	166.1 ± 12.2^{b}	104.1 ± 5.7^{a}	64.7 ± 5.4^{a}	75.1 ± 2.8^{b}	52.2 ± 2.2^{b}	39.2 ± 2.9^{a}
	40 t/ha of manure + NPK 100:90:90	13.8 ± 0.8^{a}	21.7 ± 3.0^{b}	9.2 ± 1.1^{b}	10.7 ± 1.8^{b}	289.7 ± 10.4^{c}	280.1 ± 12.0^{c}	271.7 ± 10.8^{d}	239.6 ± 12.3^{c}	101.7 ± 7.1^{c}	116.9 ± 2.2^{d}	77.9 ± 4.5^{c}	79.7 ± 5.9^{c}
Row-crop	without fertilizers	12.1 ± 1.5^{a}	10.7 ± 0.6^{a}	7.4 ± 0.9^{a}	6,2 ± 0.7^{a}	148.9 ± 12.0^{a}	157.0 ± 15.9^{a}	166.4 ± 11.8^{b}	129.9 ± 7.0^{a}	60.9 ± 8.2^{a}	76.6 ± 2.2^{b}	52.8 ± 4.2^{b}	39.8 ± 3.6^{a}
	40 t/ha of manure + NPK 100:90:90	14.2 ± 1.3^{ab}	18.7 ± 1.8^{b}	10.5 ± 2.1^{b}	10.0 ± 0.5^{b}	285.8 ± 14.2^{b}	302.8 ± 12.8^{b}	296.8 ± 5.4^{d}	269.2 ± 10.6^{c}	93.8 ± 10.2^{c}	126.8 ± 5.7^{d}	44.1 ± 4.5^{a}	64.7 ± 8.5^{b}
Grain-row crop	without fertilizers	13.7 ± 2.5^{a}	13.5 ± 0.8^{a}	7.4 ± 1.9^{a}	5.4 ± 0,9^{a}	142.6 ± 7.0^{a}	185.7 ± 12.0^{b}	195.8 ± 11.6^{b}	172.1 ± 5.1^{a}	62.4 ± 2.2^{a}	84.9 ± 2.9^{b}	47.8 ± 5.0^{a}	46.1 ± 2.2^{a}
	40 t/ha of manure + NPK 100:90:90	16.4 ± 1,0^{b}	20.2 ± 1.7^{ab}	9.3 ± 1,4^{b}	8.6 ± 0.7^{b}	295.9 ± 10.7^{d}	279.6 ± 5.4^{c}	305.3 ± 7.8^{d}	243.3 ± 14.0^{c}	99.2 ± 13.0^{c}	128.6 ± 4.5^{d}	98.1 ± 8.3^{c}	80.8 ± 3.7^{b}

Note: 1* – sugar beet seedling stage, 2–3 true leaf pairs, 2** – sugar beet harvesting period; within each crop rotation, comparisons were made between study years using ANOVA with the Bonferroni's Correction; multiple comparisons of data in rows were conducted using the Tukey's Test.

During the sugar beet seedling stage, the highest content of exchangeable potassium was observed in grain-row crop and row-crop rotations at 128.6 and 126.8 mg/kg, respectively, while in the crop rotation, it was 116.9 mg/kg. In the variants without fertilizers, the content of exchangeable potassium continued to decrease to 60.9–64.7 mg/kg of soil both at the end of rotation III in 2005–2006 and in 2021–2022 to 75.1–84.9 mg/kg. By the harvesting period of sugar beets, with the application of 40 t/ha of manure + NPK 100:90:90, the content of exchangeable potassium decreased in all crop rotation stages to 64.7–80.8 mg/kg due to its utilization by plants. In variants without fertilizers, there was a critical decrease in exchangeable potassium content to 39.2–46.1 mg/kg in 2021–2023 and 47.8–52.2 mg/kg in 2005–2006.

The yield of agricultural crops is an integral indicator of soil fertility. Among all crops in the crop rotation, sugar beets responded most to the fertilizer application system. Thus, in the variants without fertilizer application over 50 years, the yield of sugar beets decreased regardless of crop rotation stages to 16.43–17.41 t/ha (Table 4). With the application of the organo-mineral fertilizer system at the rate of 40 t/ha of manure + NPK 100:90:90, the yield of sugar beets was highest in the crop rotation (17% peas) at 44.76 t/ha, exceeding the row-crop rotation (50% peas) by 4.63 t/ha. With the application of fertilizers, the yield of roots and tops increased by 2.45–2.72 and 2.25–2.77 times, respectively, regardless of crop rotation stages.

The yield of the second crop in grain-sugar beet crop rotations for winter wheat without fertilizer application ranged 3.98 to 4.59 t/ha, which was 62.4–67.7% of the yield in the variant with NPK 90:60:90. The highest yield of winter wheat was recorded in the crop rotation with the application of NPK 90:60:90, reaching 6.78 t/ha. It is worth noting that without fertilizer application, wheat produced more straw with the grain/straw ratio of 0.9–0.7, whereas with fertilizer application, the ratio was 0.8–0.9. The yield of spring barley was at a low level as fertilizers were applied only after sugar beets. However, in the variants with post-harvest application of organo-mineral fertilizers, a significantly higher amount of straw was observed, ranging 5.07 to 5.66 t/ha, compared to 2.88–2.89 t/ha without fertilizers. Clover on green mass, grown in the crop rotation with the application of NPK 40:40:40, provided the yield of 28.15 t/ha, which exceeded the variant without fertilizers 2.27-fold. Soybean plants in the row-crop rotation showed less response to fertilizer application, with the yield difference of 1.04 t/ha, while spring vetch had a higher yield without fertilizers, which was associated with nitrogen fixation by these crops.

Table 4
Yield of main and secondary products of grain-sugar beet crop rotations depending on the fertilizer application system in the Right-Bank Forest-Steppe of Ukraine, t/ha (average for 2021–2022) (n = 6, x ± SD)

Crops	Crop Rotation	Fertilization System for Crops	Main Product, t/ha	Secondary Product, t/ha
Sugar beet	crop rotation	without fertilizers	16.43 ± 2.81	7.84 ± 1.81
		40 t/ha of manure + NPK 100:90:90	44.76 ± 2.10***	22.24 ± 2.37***
	row-crop	without fertilizers	15.93 ± 1.60	7.53 ± 1.02
		40 t/ha of manure + NPK 100:90:90	40.13 ± 3.37***	17.12 ± 1.50***
	grain-row crop	without fertilizers	17.41 ± 1.90	8.32 ± 0.88
		40 t/ha of manure + NPK 100:90:90	42.80 ± 1.66***	18.86 ± 1.25***
Winter wheat	crop rotation	without fertilizers	4.59 ± 0.61	5.08 ± 0.21
		NPK 90:60:90	6.78 ± 0.80**	9.78 ± 0.51***
	row-crop	without fertilizers	3.98 ± 0.17	4.94 ± 0.40
		NPK 90:60:90	6.30 ± 0.42***	8.95 ± 1.08**
	grain-row crop	without fertilizers	4.02 ± 0.24	4.62 ± 0.39
		NPK 90:60:90	6.44 ± 0.56**	9.33 ± 0.80***
Barley	crop rotation	without fertilizers	2.47 ± 0.31	2.89 ± 0.25
		fertilizer residues	3.70 ± 0.27**	5.07 ± 0.49**
	row-crop	without fertilizers	2.67 ± 0.32	2.89 ± 0.24
		fertilizer residues	3.95 ± 0.35**	5.66 ± 0.43***
	grain-row crop	without fertilizers	2.53 ± 0.30	2.88 ± 0.24
		fertilizer residues	3.96 ± 0.15**	5.24 ± 0.51**
Clover on green mass	crop rotation	without fertilizers	12.40 ± 0.36	–
		NPK 40:40:40	28.15 ± 2.08***	–
Soybean	row-crop	without fertilizers	2.38 ± 0.15	3.37 ± 0.51
		NPK 40:40:40	3.42 ± 0.21**	6.39 ± 1.18***
Spring vetch	grain-row crop	without fertilizers	1.89 ± 0.40	3.60 ± 1.40
		NPK 40:40:40	1.70 ± 0.31*	3.27 ± 1.11*

Note: for sugar beets, the main product is roots, and the secondary product is tops; for winter wheat, barley, soybeans, and spring vetch, the yield refers to grain, and the secondary product is straw; alfalfa was harvested for green mass; comparison was made using ANOVA between the fertilization system, where data are significant at * P *< 0.05, ** P < 0.01, *** P < 0.001.

Discussion

A multifactor stationary study enabled us to assess soil fertility indicators and the formation of sugar beet and other crop productivity, depending on their concentration in crop rotation, the structure of crop rotations over 50 years. At the Bila Tserkva research station, the study of the influence of crop rotation structure on soil humus status had been conducted since 1949. According to the initial results of humus content reduction, "from the application of 6 t/ha of NPK 20:21:20 manure per hectare, depending on the structure of crop rotations, humus content decreased by 0.1–0.4%. In the second and third rotations, the manure rate increased to 12 t/ha, but in the crop rotation without perennial grasses (50% row crop), the reduction in humus content over 15 years was 0.33%" (Bysovetskyi et al., 1974). Detailed studies by the Institute of Bioenergy Crops and Sugar Beets of the National Academy of Agrarian Sciences showed 0.8% decrease in humus content over 16 years on less humus-rich chernozem soil (Veselopodilskyi research station) without fertilizer application in the plowed and 0.2% in the sub-plowed soil layers. In the row-crop rotation (60% row crop), humus content decreased by 0.62% over 20 years in the 0–30 cm layer and by 0.25% in the 30–50 cm layer. On heavy loamy chernozem soil (Verkhniatska research station), humus losses over the first 16 years of the experiment under unfertilized conditions amounted to 0.62% (Barshtein et al., 2002).

The results of our research are consistent with the study by Petrova (2004), when during two rotations from 1973–1993, the humus content in the 0–60 cm layer of soil in the crop rotation variant without fertilizers decreased by 0.34%, in the row-crop rotation – by 0.45%, in the grain-row crop rotation – by 0.29%, while after applying 6 t/ha of manure + NPK 50:66:66 per hectare of crop rotation area, the reduction was by 0.03 and 0.10%, and in the grain-row crop rotation, there was 0.16% increase. It should be noted that the humus content was determined in the field of the last crop of the crop rotation – barley, when its humification was quite low (Petrova, 2004).

To reduce humus losses, the manure dose for sugar beets was increased to 30 t/ha, and since 2006 to 50 t/ha. According to foreign researchers, such a dose of organic fertilizers, along with plowing in of crop residues, stabilizes soil fertility (Götze et al., 2016; Petek et al., 2019; Heydarzadeh et al., 2021; Rašovský et al., 2022). Since 2006, Tsvey et al. (2018) restructured 10-field crop rotations into 6-field ones, reducing the share of sugar beets to 17%, introducing oats and vetch cover crop, and optimizing the fertilizer application system. With the application of 9 t/ha of manure + NPK 43:43:43 per hectare of crop rotation area, the humus content in the crop rotation reached 3.55%, in the row-crop rotation – 3.34%, in the grain-row crop rotation – 3.45% (Tsvey et al., 2018). However, as of 2021–2022, the highest humus losses were observed in the row-crop rotation, which can be explained by introduction of sunflower, decrease in the number of forage crops, and overall deterioration of the soil's physical and chemical indicators.

Fertilizer application leads to decline in soil pH and increase in hydrolytic acidity (Havryshko et al., 2022; Syromyatnikov, 2023). However, in our conditions, for chernozems, the typical leaching trace should be considered as both leaching of Ca and Mg from the plowed layer of soil and its utilization by sugar beet plants. Despite the use of nitrogen by plants, its amount increases under the organo-mineral fertilizer application system. At the end of the sugar beet vegetation period, mineral nitrogen decreases 1.72–2.50 times due to its utilization by plants and the attenuation of mineralization processes in the soil (Tsvey et al., 2018; Tanchyk et al., 2023). In the variants with the organo-mineral fertilizer application system, the content of available phosphates increased 1.98–2.30 times during the sugar beet emergence and harvesting periods in the crop rotation, in the row-crop rotation – 1.93–2.07 times, and the lowest increase was in the grain-row crop rotation – 1.41–1.51 times, compared to the variant without fertilizer application. Additionally, manure as an organic fertilizer contributes to increase in mobile phosphorus compounds in the soil due to its mineralization, as well as the low utilization coefficient of phosphorus by crops in crop rotation (Kusi et al., 2021; Ali et al., 2023).

Contrary to mobile phosphorus, the content of exchangeable potassium critically decreased during the sugar beet harvesting period without fertilizer application, which can be explained by its maximum utilization by sugar beet plants. With long-term potassium application as part of complete mineral fertilizers and manure, its content in typical chernozems ranged 116.9–128.6 mg/kg of soil during the emergence period to 64.7–80.8 mg/kg of soil during the sugar beet harvesting period, due to its high content and dynamic equilibrium between different forms of potassium, the soil's ability to replenish reserves of mobile potassium compound as plants uses them during the vegetation period (Martyniuk, 2020).

Long-term cultivation of sugar beet without fertilizer application significantly reduced their productivity even on fertile chernozems, as confirmed by numerous studies (Barshtein et al., 2002; Ahmad et al., 2017; Martyniuk, 2020). According to the results of our research, sugar beets are the most demanding in terms of soil fertility, and the yield of roots using the organo-mineral fertilizer application system exceeded the variant without fertilizers by 2.45–2.72 times. The next crop in the crop rotation, barley, regardless of fertilization, showed low productivity, which was associated with significant shortage of productive moisture reserves in the soil (Makukh et al., 2023). Additionally, sugar beet plants consumed a significant amount of nitrogen from the soil. The yield of the precursor of sugar beets, winter wheat, with fertilizer application exceeded that without fertilizers by 2.19–2.45 t/ha. Weather conditions (sufficient moisture and temperature regime in autumn) had a greater impact on wheat yield, while nitrogen availability in the soil remained critical (Tsvey et al., 2020; Hlisnikovský, 2023). The yields of soybeans and spring barley were significantly independent of fertilization, while clover required significantly higher productive reserves of moisture in the soil.

Conclusions

Growing agricultural crops without application of fertilizers led to decrease in humus content in chernozem soils. Under such conditions, organic matter input occurs solely through root residues and post-harvest residues, leading to increased humus mineralization processes. Over 50 years in crop rotations with 30% saturation of sugar beets, humus reserve lost in the plowed layer in the crop rotation and grain-row crop rotation amounted to 31.8 and 32.1 t/ha, or 23.1% and 23.4% of the initial reserves, with the highest losses noted in the row-crop rotation – 35.7 t/ha, or 26.1% of the initial reserves. Meanwhile, humus content decreased by 0.89%, 0.90%, and 1.00%, due to both increased organic matter mineralization processes in the soil and fewer crop residues.

In grain-sugar beet rotations with organo-mineral fertilizer application systems, soil acidity increased, and the hydrolytic acidity index increased 1.46–1.69 times in rapeseed and grain-rapeseed rotations. In the variants without fertilizers, there was only a tendency towards soil acidification, with decrease in hydrolytic acidity. Applying 40 t/ha of manure + NPK 100:90:90 for sugar beets promoted accumulation of mineral nitrogen in the plowed soil layer, exceeding the variant without fertilizers 1.52–1.74 times depending on the crop rotation cycles.

Through long-term use of typical leached chernozem without fertilizer application in grain-sugar beet rotations, the content of mobile phosphorus during the sugar beet emergence period decreased to 141.8–185.7 mg/kg of soil, while with fertilizer application, it increased to 280.1–302.8 mg/kg of soil, due to additional inputs from manure and low utilization by crops. Exchangeable potassium content significantly decreased regardless of fertilization system, which was attributed to utilization by plants.

Yield of sugar beet increased to 44.76 t/ha in crop rotation with organo-mineral fertilizer application in the dose of 40 t/ha of manure + NPK 100:90:90, exceeding the row-crop rotation by 4.63 t/ha, and in the variants without fertilizers by 2.45–2.72 times. The productivity of other crops in the rotation depended more on fertilizer application and weather conditions.

The authors declare no conflicts of interest.

References

Ahmad, I., Ahmad, B., Ali, S., Fang, H. Q., Kamran, M., & Bilegjargal, B. (2017). Nutrients management strategies to improve yieldand quality of sugar beet in semi-arid regions. Journal of Plant Nutrition, 40(2), 2109–2115.

Ali, A. M., Mahdy, A. Y., Al-Sayed, H. M., & Bayomi, K. M. (2023). Phosphorus sources and sheep manure rertilization for soil properties enhancement and sugar beet yield. Journal of Crop Health, 75, 2785–2795.

Baliuk, S. A., Danylenko, A. S., & Furdychko, O. I. (2017). Appeal to state leadership concerning overcoming crisis situation in the sphere of protection of lands. Bulletin of Agricultural Science, 11, 5–8.

Baliuk, S., Nosko, B., & Vorotyntseva, L. (2018). Regulation of fertility of soils and efficiency of fertilizers in conditions of climate fluctuations. Bulletin of Agricultural Science, 3, 5–12.

Barshtein, L. A., Shkaredny, I. S., & Yakymenko, V. M. (2002). Sivozminy, obrobitok gruntu ta udobrennia v zonakh buriakosiiannia [Crop rotations, soil cultivation and fertilization in beet-growing zones]. Tenar, Kyiv (in Ukrainian).

Bysovetskyi, T. Y., Petrova, O. T., & Fedorenko L. V. (1974). Rezultaty analitychnykh doslidzhen u statsionarnykh ta tymchasovykh doslidakh na Bilotserkivska doslidno-selektsiina stantsiia [Results of analytical studies in stationary and temporary experiments in Bilotserkiv selection station]. In: Buzanov, I. F. (Ed.). Pidvyshchennia rodiuchosti gruntiv raioniv buriakosiiannia [Increasing soil fertility in areas where sugar beets are grown]. All-Union Scientific Research Institute for Sugar Beet, Kyiv. Pp. 165–173 (in Ukrainian).

Gamayunova, V., Khonenko, L., Baklanova, T., Kovalenko, O., & Pilipenko, T. (2020). Suchasni pidkhody do zastosuvannia mineralnykh dobryv za zberezhennia hruntovoi rodiuchosti v umovakh zminy klimatu [Modern approaches to use of the mineral fertilizers and preservation of soil fertility in the conditions of climate change]. Scientific Horizons, 87, 89–101 (in Ukrainian).

Götze, P., Rücknagel, J., Jacobs, A., Märländer, B., Koch, H.-J., Holzweißig, B., Steinz, M., & Christen, O. (2016). Sugar beet rotation effects on soil organic matter and calculated humus balance in Central Germany. European Journal of Agronomy, 76, 198–207.

Havryshko, O., Olifir, Y., Gabryiel, A., & Partyka, T. (2022). Transformatsiia ahrokhimichnykh vlastyvostei yasno-siroho lisovoho poverkhnevo ohleienoho gruntu za tryvaloho periodu silskohospodarskoho vykorystannia [Transformation of agrochemical properties of light-gray forestal surface-gleyed soil during long-term agricultural use]. Peredčirne ta Girs'ke Zemlerobstvo i Tvarinnictvo, 71(2), 85 (in Ukrainian).

Hergert, G. W. (2010). Sugar beet fertilization. Sugar Tech, 12, 256–266.

Heydarzadeh, S., Gitari, H., Rahimi, A., Khiavi, K. H., Khiavi, H. K., Maitra, S., & Türkoğlu, A. (2021). Yield and quality traits of field-grown sugar beet (*Beta vulgaris* L.) in response to foliar application of micronutrients and different levels of manure. International Journal of Bioresource Science, 8(2), 109–118.

Hlisnikovský, L., Menšík, L., & Kunzová, E. (2023). Development and the effect of weather and mineral fertilization on grain yield and stability of winter wheat following alfalfa-analysis of long-term field trial. Plants, 12(6), 1392.

Hospodarenko, H. M., Boiko, V. P., Prokopchuk, I. V., & Stasinievych, O. Y. (2019). Vmist i balans humusu u grunti za riznykh doz i spivvidnoshen' mineralnykh dobryv u pol'ovii sivozmini [Humus content and balance in the soil with different doses and ratios of mineral fertilizers in field crop rotation]. Myronivka Bulletin, 8, 108–122 (in Ukrainian).

Hospodarenko, H., Prokopchuk, I., Prokopchuk, S., & Trus, A. (2018). Humus content in a podzolized chernozem after a long-term application of fertilizers in a field crop rotation. Agronomy Research, 16(3), 728–736.

Körschens, M., Albert, E., Armbruster, M., Barkusky, D., Baumecker, M., Behle-Schalk, L., Bischoff, R., Čergan, Z., Ellmer, F., Herbst, F., Hoffmann, S., Hofmann, B., & Kismanyoky T. et al. (2013). Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: Results from 20 European long-term field experiments of the twenty-first century. Archives of Agronomy and Soil Science, 59(8), 1017–1040.

Kusi, Y. N. O., Stevens, W. B., Sintim, H. Y., Garcia, A., & Mesbah, A. O. (2021). Phosphorus fertilization and enhanced efficiency products effects on sugar beet. Industrial Crops and Products, 171, 113887.

Makukh, Y., Remeniuk, S., Moshkivska, S., Riznyk, V., Zatserkovna, N., Rudnyk-Ivashchenko, O., & Buzynnyi, M. (2023). Water use of sugar beet and spring barley in different crop rotations and fertilisation systems in chernozem in Ukraine. Zemdirbyste-Agriculture, 110(2), 121–128.

Markovska, O. Y., Maliarchuk, M. P., Maliarchuk, V. M., Ivaniv, M. O., & Dudchenko, V. V. (2020). Modelling of humus balance under different systems of basic tillage and soil fertilization in crop rotations. Ukrainian Journal of Ecology, 10(5), 291–295.

Martyniuk, A. T. (2020). Pozhyvnyi rezhym hruntu i vrozhainist buriaku tsukrovoho pislia tryvaloho zastosuvannia dobryv u polovii sivozmini [Soil nutrient regime and sugar beet yield after long-term application of

fertilizers in crop rotation]. Bulletin of Uman National University of Horticulture, 1, 42–46 (in Ukrainian).
Martyniuk, A. T., Hospodarenko, H. M., & Stasinievych, O. Y. (2023). Dynamika vrozhainosti buriaku tsukrovoho v lankakh polovoi sivozminy za tryvaloho zastosuvannia dobryv [Dynamics of the productivity of sugar beet during the long-term use of fertilizers in field crop rotation in the right-bank Forest-Steppe]. Bulletin of Uman National University of Horticulture, 1, 128–138 (in Ukrainian).
Petek, M., Toth, N., Pecina, M., Karažija, T., Lazarević, B., Palčić, I., Veres, S., & Ćustić, M. H. (2019). Beetroot mineral composition affected by mineral and organic fertilization. PLoS One, 14(9), e0221767.
Petrova, O. T. (2004). Vmist humusu v grunti na pochatku i v kinets rotatsii sivozminy [The content of humus in the soil at the beginning and at the end of the crop rotation]. In: Roik, M. V. (Ed.). Tsukrovi Buriaky. Kyiv, Agrarna Nauka. Pp. 6–7 (in Ukrainian).
Rašovský, M., Pačuta, V., Ducsay, L., & Lenická, D. (2022). Quantity and quality changes in sugar beet (*Beta vulgaris* provar. *altissima* Doel) induced by different sources of biostimulants. Plants, 11(17), 2222.
Symochko, L., Demyanyuk, O., Crisan, V., & Dinca, L. (2024). Microbial transformation of soil organic matter under varying agricultural management systems in Ukraine. Frontiers in Microbiology, 14, 1287701.
Syromyatnikov, Y. (2023). Physico-chemical indicators of soil condition depending on sugar beet growing technology. Agriculture and Plant Sciences: Theory and Practice, 3, 59–69.
Tanchyk, S. P., Tsentylo, L. V., & Tsyuk, O. A. (2022). Balance of nitrogen, phosphorus, potassium in the soil depending on farming systems in crop rotation. Agrology, 5(3), 92–96.
Truskavetskiy, R., Zubkovskaya, V., & Khyzhniak, I. (2020). Transformatsiia ahrokhimichnykh vlastyvostei yasno-siroho lisovoho poverkhnevo ohleienoho gruntu za tryvaloho periodu silskohospodarskoho vykorystannia [Innovative models of soil fertility elements management]. Bulletin of Lviv National University: Agronomy, 24, 181–186 (in Ukrainian).
Tsvey, Y. P. (2014). Rodiuchist' gruntiv i produktyvnist' sivozmin [Soil fertility and crop rotation productivity]. CPP Comprint, Kyiv (in Ukrainian).
Tsvey, Y. P., Bondar, S. O., & Kisilevska, M. O. (2016). Content of humus of black earth depending on fertilizer system in short-crop rotations. Bulletin of Agricultural Science, 9, 5–9.
Tsvey, Y. P., Tyshchenko, M. V., Filonenko, S. V., & Liashenko, V. V. (2018). Formuvannia pozhyvnoho rezhymu gruntu v poli tsukrovykh buriakiv zalezhno vid yikh udobrennia v korotkorotatsiinii plodozminnii sivozmini [Formation of nutrient regime of soil in the field of sugar beets depending on their fertilization in short-term crop rotation]. Scientific Progress and Innovations, 4, 43–50 (in Ukrainian).
Tsvey, Y., Ivanina, R., & Senchuk, S. (2020). Pozhyvnyi rezhym chornozemu vyluhuvanoho ta produktyvnist' zernovoi lanky za tryvaloho udobrennia sivozminy [Nutrient status of leached chernozem and productivity of grain link after long-term fertilizing]. Bulletin of Agricultural Science, 98(3), 5–12 (in Ukrainian).
Varga, I., Jović, J., Rastija, M., Markulj Kulundžić, A., Zebec, V., Lončarić, Z., Iljkić, D., & Antunović, M. (2022). Efficiency and management of nitrogen fertilization in sugar beet as spring crop: A review. Nitrogen, 3, 170–185.
Zaryshniak, A. S., Baliuk, S. A., Lisovyi, M. V., & Komarista, A. V. (2012). Balans humusu i pozhyvnykh rechovyn u gruntakh Ukrainy [Balance of humus and nutrients in the soils of Ukraine]. Bulletin of Agricultural Science, 1, 28–32 (in Ukrainian).