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Long-term effects of fertilisation systems on soil nutrient status, soil organic carbon content and crop productivity in a typical Chernozem under different crop rotations

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Abstract: The aim of this study was to evaluate the long-term effects of fertilisation systems and crop rotation structure on soil nutrient status, organic carbon (OC) content and stocks, and crop productivity in a typical Chernozem. The study was conducted during 2019–2024 as part of a long-term field experiment established in 1976 at the Bila Tserkva Experimental Breeding Station in the Right-Bank Forest-Steppe of Ukraine. Four fertilisation treatments were compared in cereal-fodder-row (CFR) and cereal-row-crop (CRC) rotations: unfertilised since 1976, mineral fertilisation with straw incorporation, mineral + cattle manure fertilisation, and organic fertilisation. Soil mineral N, plant-available P, exchangeable K, OC content, and OC stocks were determined in the 0–30 cm soil layer. Crop yields were assessed for winter wheat, sugar beet and spring barley. The mineral + cattle manure treatment generally maintained favourable soil nutrient conditions and resulted in the highest OC content and stocks in both crop rotations, reaching 1.98% and 70.8 t C/ha in the CFR rotation and 1.77% and 63.2 t C/ha in the CRC rotation. However, the higher nutrient inputs under this treatment did not result in proportionally higher residual availability of all nutrients. Under sugar beet, its clearest post-harvest advantage was observed for soil mineral N, whereas exchangeable K was not consistently higher than under the other fertilised treatments, and plant-available P in the CFR rotation did not differ significantly between the mineral + straw and mineral + cattle manure treatments. The highest mean yields of winter wheat, sugar beet and spring barley were generally obtained under the mineral + cattle manure treatment. Sugar beet root yield reached 46.9 t/ha in the CFR crop rotation and 42.2 t/ha in the CRC rotation, compared with 18.8 and 17.1 t/ha, respectively, in the unfertilised treatments. The results demonstrate that combining organic and mineral nutrient sources with crop residue return and an appropriate crop rotation structure is an effective strategy for maintaining typical Chernozem fertility and sustaining crop productivity under unstable moisture conditions.

Keywords: soil fertility; soil-plant system; long-term experiment; available nutrient reserve; clover; soybean

Maintaining soil fertility has become increasingly important due to declining use of organic fertiliser, rising mineral fertiliser costs, soil degradation, and nutrient imbalances in the soil-plant system. Approximately one-third of the world's soils are estimated to be moderately or severely degraded

because of erosion, organic matter depletion, nutrient imbalance, salinisation, contamination, acidification, biodiversity loss, compaction, and deterioration of the soil water regime. Soil fertility management should therefore be regarded as an agronomic, environmental, and economic priority (Smith et al. 2024).

An effective approach to stabilising soil fertility is to integrate balanced fertilisation, crop rotation, crop residue return, and post-harvest green manure crops. Crop rotation influences organic matter cycling, nutrient balances, microbial communities, and soil organic carbon (OC) accumulation. Its effectiveness can be enhanced by including crops with contrasting root systems, residue production, and nutrient requirements (Šimon et al. 2024, Yang et al. 2024).

Long-term experiments indicate that organo-mineral fertilisation is generally more balanced than the exclusive use of mineral fertilisers. Combining organic and mineral nutrient sources with crop residues and green manures helps maintain soil organic matter, improve soil physical properties, stimulate microbial activity, and sustain crop productivity (Götze et al. 2016, Barłóg and Grzebisz 2025, Barłóg et al. 2025, Lamlom et al. 2025).

Crop residues, including straw, maize stalks, sugar beet tops, and cereal and grain legume residues, are an important source of OC and nutrients returned to the soil. Their incorporation can improve soil structure, water retention, biological activity, and OC accumulation, especially where manure availability is limited. This is particularly relevant for typical Chernozems of the Forest-Steppe zone of Ukraine, where long-term intensive cultivation may reduce soil organic matter and available nutrient reserves. Therefore, an integrated organo-mineral system combining rational crop rotation, crop residue return, post-harvest green manure crops, and differentiated mineral fertilisation can help maintain soil fertility, sustain crop productivity, reduce nutrient losses, and improve the environmental and economic sustainability of agriculture under unstable moisture conditions.

MATERIAL AND METHODS

Site description and experimental conditions.

The study was conducted during 2019–2024 in the Right-Bank Forest-Steppe of Ukraine at the Bila Tserkva Experimental Breeding Station. The soil at the experimental site was a typical deep, leached, medium-loamy Chernozem. According to the WRB/FAO, this soil can be classified as Luvic Chernozem (Loamic,

Humic). Plough layer composition: coarse particles 49.8–58.2%, clay 30.5–34.2%, silt 18.6–24.21% and sand 9.8–19.1%. The organic carbon in the 0–30 cm soil layer ranged from 1.74% to 2.21%. Plant-available phosphorus and potassium were extracted with 0.5 mol/L acetic acid and determined by the modified Chirikov method in accordance with DSTU 4115:2002, using colourimetry for phosphorus and flame photometry for potassium. Their contents were 153–170 and 64–78 mg/kg soil, respectively. Alkaline hydrolysable nitrogen was determined by the Cornfield method after alkaline hydrolysis with NaOH, followed by absorption of released ammonia in boric acid and titrimetric determination; its content was 120–140 mg/kg soil. Soil pH was determined potentiometrically in 1 mol/L KCl solution and was 6.4; the thickness of the OC horizon was 80 cm.

The long-term stationary experiment included six different field crop rotations under different fertilisation systems. The crop sequences were as follows: (1) vetch-oat mixture – winter wheat – sugar beet – barley with undersown clover – clover – winter wheat, representing a crop rotation with a high share of fodder crops (cereal-fodder-row crop rotation (CFR)); and (2) vetch-oat mixture – winter wheat – sugar beet – barley – soybean – sunflower, representing a cereal-row-crop rotation (CRC). Crop cultivation technology was generally accepted for the Central Forest-Steppe zone of Ukraine. All crops were grown under rainfed conditions, without irrigation. The fertilisation systems used in the experiment are presented in Table 1.

For winter wheat, nitroammophoska (NPK 16:16:16) was applied at sowing at a rate of 375 kg/ha, supplying 60.0 kg N/ha, 26.2 kg P/ha, and 49.8 kg K/ha. An additional 90 kg/ha of ammonium nitrate (34% N), equivalent to 30.6 kg N/ha, was applied as a top-dressing. For sugar beet, ammonium nitrate, granular superphosphate, and potassium chloride were broadcast at rates equivalent to 100 kg N/ha, 39.3 kg P/ha and 74.7 kg K/ha. These rates corresponded to 300 kg/ha of ammonium nitrate (34% N), 320 kg/ha of granular superphosphate (12.22% P), and 145 kg/ha of potassium chloride (51.47% K). For clover and soybean, nitroammophoska (NPK 16:16:16) was applied at a rate of 250 kg/ha, supplying 40 kg N/ha, 17.5 kg P/ha and 33.2 kg K/ha. Semi-rotted cattle manure was applied to sugar beet at a rate of 40 t/ha, supplying approximately 200 kg N/ha, 100 kg P/ha, and 240 kg K/ha, based on nutrient contents of 5.0 kg N, 2.5 kg P, and 6.0 kg K per tonne of manure.

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Table 1. Fertilisation systems used in the crop rotations

Crop	Fertiliser system			
	unfertilised	mineral + straw	mineral + cattle manure	organic
Vetch-oat mixture	no fertilisers were applied			
Winter wheat		90 kg N/ha + 26.2 kg P/ha + 49.8 kg K/ha	90 kg N/ha + 26.2 kg P/ha + 49.8 kg K/ha	
Sugar beet		100 kg N/ha + 39.3 kg P/ha + 74.7 kg K/ha + winter wheat straw + 40 kg N/ha	40 t/ha cattle manure + 100 kg N/ha + 39.3 kg P/ha + 74.7 kg K/ha	40 t/ha cattle manure
Barley	without fertilisers since 1976	residual effect of mineral fertilisation + sugar beet tops	residual effect of mineral + cattle manure fertilisation	
Clover/soybean*		40 kg N/ha + 17.5 kg P/ha + 33.2 kg K/ha + straw	40 kg N/ha + 17.5 kg P/ha + 33.2 kg K/ha	residual effect of organic fertilisation
Winter wheat/sunflower*		90 kg N/ha + 26.2 kg P/ha + 49.8 kg K/ha	90 kg N/ha + 26.2 kg P/ha + 49.8 kg K/ha	
Mean annual input per ha of crop rotation area		53.3 kg N/ha + 18.2 kg P/ha + 34.6 kg K/ha	6.7 t/ha cattle manure + 53.3 kg N/ha + 18.2 kg P/ha + 34.6 kg K/ha	6.7 t/ha cattle manure

*The fertilisation system for clover in the cereal-fodder-row crop rotation (CFR) was the same as that for soybean in the CRC rotation. Similarly, the fertilisation system for winter wheat in the cereal-row-crop rotation (CFR) was the same as that for sunflower in the CRC rotation. **A total of 320 kg N/ha, 109.2 kg P/ha, and 207.5 kg K/ha was applied over the entire crop rotation

The unfertilised control plots had received no fertilisers since 1976. The primary tillage system comprised mouldboard ploughing to a depth of 28–30 cm for sugar beet and 20–22 cm for winter wheat and maize, whereas shallow disking to a depth of 12–15 cm was used for the other crops. Registered cultivars were grown in the experiment: sugar beet cv. Constanta, barley cv. Odyssey, and soybean cv. Apollo. Soil OC was determined after barley harvest. Crop yields were determined from 100 m² harvest plots in three replications and expressed in t/ha.

Soil sampling and analytical methods. The methods used for soil analysis have remained unchanged since the establishment of the long-term field experiment. Mineral nitrogen content (NO_3^- -N + NH_4^+ -N) was determined according to DSTU ISO 14255:2005 after extraction of nitrate nitrogen, ammonium nitrogen, and total soluble nitrogen from air-dried soil with calcium chloride solution, followed by colourimetric determination. Plant-available phosphorus and potassium were extracted with 0.5 mol/L acetic acid and determined using the modified Chirikov method in accordance with DSTU 4115:2004; phosphorus was measured colourimetrically, and potassium by

flame photometry. OC content was calculated from OC determined by the Tyurin method according to DSTU 4289:2004, based on oxidation of organic matter with potassium dichromate in sulfuric acid, followed by titrimetric determination. Soil fertility parameters in the sugar beet plots were determined at two growth stages: the stage of 2–3 pairs of true leaves and harvest. For the other crops, these parameters were determined at harvest. Soil samples were collected from the 0–30 cm layer. OC stocks in the 0–30 cm soil layer were calculated using a mean soil bulk density of 1.19 g/cm³.

Statistical analysis. Yield data for winter wheat collected in 2019–2021, sugar beet in 2020–2022, and spring barley in 2021–2023 were subjected to analysis of variance. Crop yield was analysed using two-way ANOVA to evaluate the effects of fertilisation treatment, crop rotation, and their interaction, with both factors treated as fixed effects. Differences among crop rotation × fertilisation treatment combinations were evaluated using Tukey's *HSD* (honestly significant difference) test at $P \leq 0.05$.

For sugar beet, soil nutrient contents were analysed using three-way ANOVA to assess the effects of crop

rotation, fertilisation system, sampling time (2–3 true leaf pairs and harvest), and their interactions. Crop rotation, fertilisation system, and sampling time were treated as fixed factors, whereas year was included in the model as a blocking factor. All two-way interactions and the three-way interaction among crop rotation, fertilisation system, and sampling time were tested. For barley and legume crops, soil nutrient contents were analysed using two-way ANOVA to assess the effects of crop rotation, fertilisation system, and their interaction, with year included as a blocking factor. When significant effects were detected, means were compared using Tukey's *HSD* test at $P \leq 0.05$. Different lowercase letters indicate significant differences according to Tukey's *HSD* test, whereas means sharing at least one letter are not significantly different. Soil OC content was analysed using two-way ANOVA with crop rotation and fertilisation system as fixed factors, and year as a blocking factor. The crop rotation $\times$ fertilisation system interaction was also tested. Mean separation was performed using Tukey's *HSD* test at $P \leq 0.05$.

Weather condition. Weather conditions during 2020–2024 differed considerably from the long-term average and were characterised by warmer winters, uneven precipitation distribution, and periodic moisture deficits. The long-term mean annual precipitation at the Bila Tserkva meteorological station is 526 mm. During the study period, annual precipitation ranged from 481 mm to 567 mm: 2020 and 2021 were wetter than the long-term average, whereas 2022–2024 were drier than the long-term average. The greatest temperature deviations were recorded in winter and summer, especially in 2022 and 2024, when elevated air temperatures coincided with insufficient or uneven rainfall. Overall, the weather conditions during 2020–2024 were characterised by marked interannual variability in temperature and precipitation, with a general tendency toward warmer conditions and periodic moisture deficits. These contrasting hydrothermal conditions likely affected soil moisture availability, nutrient transformation processes, organic matter dynamics, and crop productivity, and therefore should be considered when interpreting the effects of fertilisation systems and crop rotations.

RESULTS

Dynamics of available nutrient elements in soil under sugar beet crops. The contents of mineral N, plant-available phosphorus, and exchangeable po-

tassium in the typical Chernozem under sugar beet were affected by crop rotation, fertilisation system, and crop growth stage. In general, the contents of all three nutrients decreased from the stage of 2–3 pairs of true leaves to harvest, reflecting their uptake by sugar beet during the growing season.

In the CFR crop rotation, the highest initial mineral N content was recorded under the mineral fertilisation system with straw incorporation, at 29.1 mg N/kg soil (Figure 1), exceeding the unfertilised treatment by 14.9 mg N/kg (104.9%). The corresponding values under the mineral + cattle manure and organic treatments were 21.7 and 15.3 mg N/kg soil, respectively. By harvest, mineral N content had decreased to 5.6–10.7 mg N/kg soil, with the highest residual content recorded under the mineral + cattle manure treatment.

In the CRC crop rotation, initial mineral N contents were lower than in the CFR crop rotation. They ranged from 10.7 mg N/kg soil in the unfertilised treatment to 18.7 mg N/kg soil under the mineral + cattle manure treatment, exceeding the control by 8.0 mg N/kg (74.8%). The mineral fertilisation system with straw incorporation and the organic system resulted in 14.7 and 14.1 mg N/kg soil, respectively. Mineral N content declined by harvest but generally remained higher in the fertilised treatments than in the unfertilised control. Despite receiving the highest overall N input, the mineral + cattle manure treatment showed its clearest advantage only in the post-harvest mineral N content, which was higher than under the other fertilisation treatments.

Plant-available phosphorus also responded to fertilisation. In the unfertilised treatments, the initial plant-available P content was 61 mg P/kg soil in the CFR crop rotation and 70 mg P/kg soil in the CRC crop rotation (Figure 2). In the CFR crop rotation, mineral fertilisation with straw incorporation, mineral + cattle manure, and organic fertilisation increased plant-available P content to 119, 120, and 99 mg P/kg soil, respectively. In the CRC crop rotation, the highest initial value, 138 mg P/kg soil, was recorded under the mineral + cattle manure treatment.

Although plant-available P contents declined by harvest, fertilised treatments generally maintained higher values than the unfertilised control. In the CFR crop rotation, post-harvest P did not differ significantly between the mineral + straw and mineral + cattle manure treatments despite the higher P input in the latter, indicating that soil P availability was not proportional to the amount applied.

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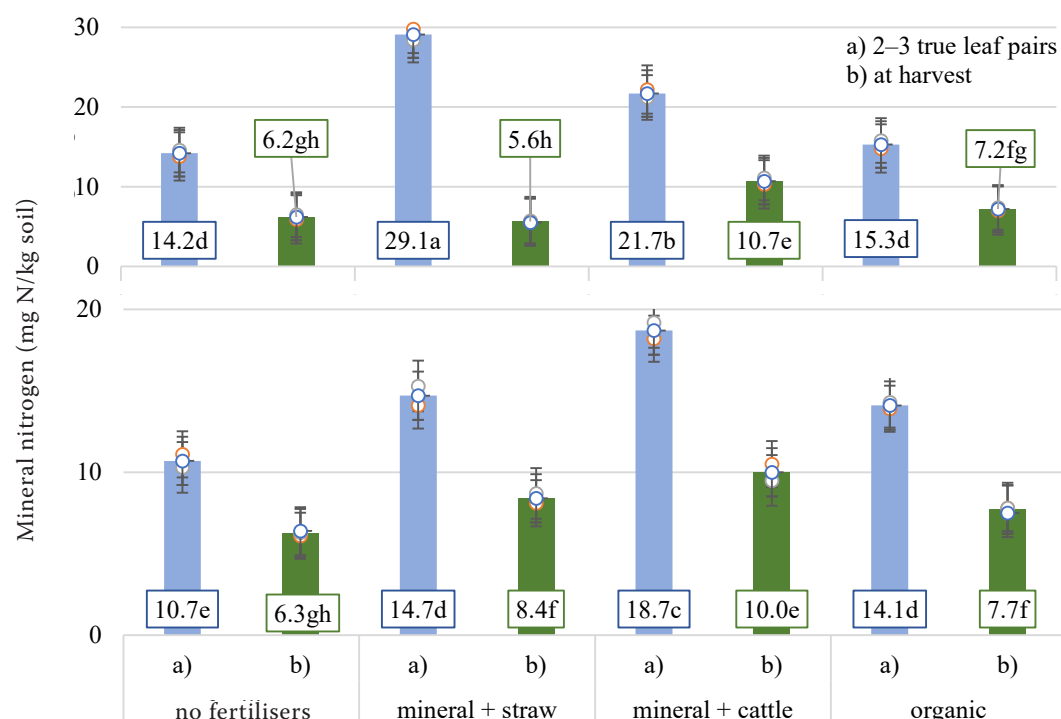


Figure 1. Dynamics of mineral nitrogen (N) content in the 0–30 cm soil layer under sugar beet in different crop rotations: CFR (cereal-fodder-row crop rotation), upper panel; CRC (cereal-row-crop rotation) lower panel

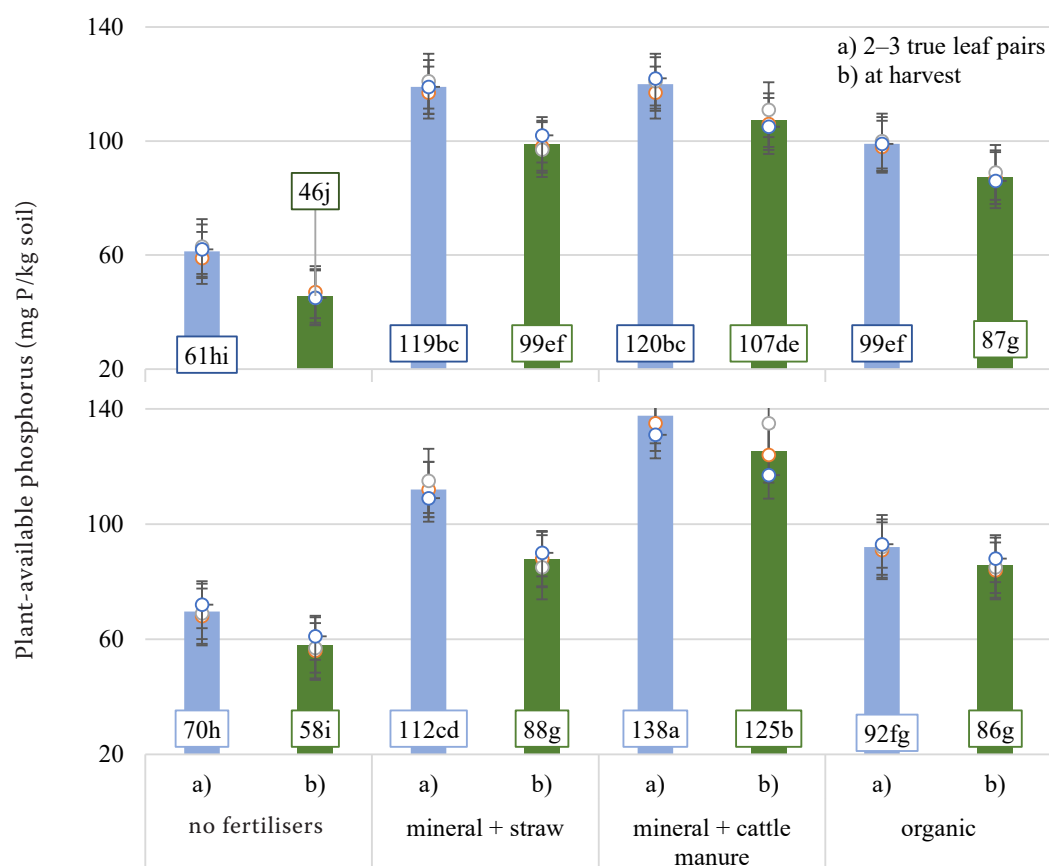


Figure 2. Dynamics of plant-available phosphorus (P) content in the 0–30 cm soil layer under sugar beet in different crop rotations: CFR (cereal-fodder-row crop rotation), upper panel; CRC (cereal-row-crop rotation) lower panel

At the stage of 2–3 pairs of true leaves, exchangeable K contents in the unfertilised treatments were 71 and 72 mg K/kg soil in the CFR and CRC crop rotations, respectively (Figure 3). In the CFR crop rotation, the highest initial exchangeable K content was recorded under the organic treatment, at 119 mg K/kg soil, compared with 111 mg K/kg soil under the mineral system with straw incorporation and 101 mg K/kg soil under the mineral + cattle manure treatment. In the CRC crop rotation, the mineral + cattle manure treatment produced the highest value, at 121 mg K/kg soil, whereas the mineral fertilisation with straw incorporation and organic treatments resulted in 84 and 77 mg K/kg soil, respectively.

Exchangeable K contents decreased in all treatments by harvest. Despite receiving the highest total K input, the mineral + cattle manure treatment did not consistently increase post-harvest soil exchangeable K compared with the other fertilisation treatments. Thus, the soil K response was not proportional to the amount of K applied, which may reflect intensive K uptake by sugar beet as well as transformations

and redistribution of potassium within the soil-plant system during the growing season.

Overall, the unfertilised treatments generally had the lowest nutrient contents, indicating gradual depletion of plant-available nutrient pools under long-term cultivation without nutrient replenishment. However, the responses of individual nutrients were not directly proportional to total nutrient inputs. Although the mineral + cattle manure treatment received the highest overall inputs of N, P, and K, its clearest advantage at harvest was observed for soil mineral N. In contrast, exchangeable K was not consistently increased relative to the other fertilised treatments, while in the CFR crop rotation, post-harvest plant-available P did not differ significantly between the mineral + straw and mineral + cattle manure treatments. These findings indicate that residual nutrient availability was determined not only by fertiliser inputs but also by crop nutrient uptake and soil nutrient transformation processes.

Residual effects of fertilisation systems on soil N, P and K contents under barley. Under spring barley,

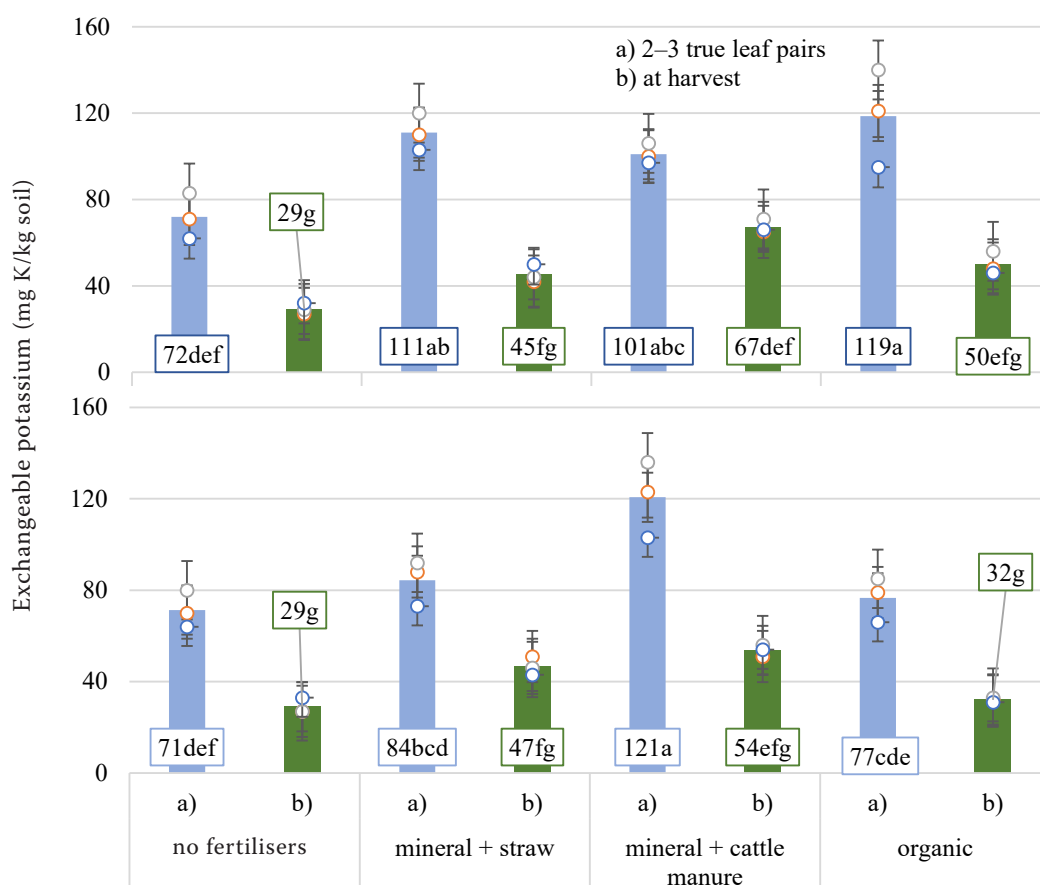


Figure 3. Dynamics of exchangeable potassium (K) content in the 0–30 cm soil layer under sugar beet in different crop rotations: CFR (cereal-fodder-row crop rotation), upper panel; CRC (cereal-row-crop rotation) lower panel

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mineral N content reached 10.8 mg N/kg soil under the residual effects of both mineral fertilisation with straw incorporation and the mineral + cattle manure system in the CFR crop rotation. In the CRC crop rotation, the corresponding values were 10.0 and 11.6 mg N/kg soil, respectively (Figure 4). No significant differences among fertilisation systems were detected.

In the CFR crop rotation, plant-available P content increased from 71 mg P/kg soil in the unfertilised treatment to 112 mg P/kg soil under mineral fertilisation with straw incorporation and 133 mg P/kg soil under the mineral + cattle manure treatment. However, the mineral + cattle manure treatment did not differ significantly from the other fertilised treatments. A similar pattern was observed in the CRC crop rotation, where no significant differences were found among the fertilised treatments, except that the mineral + cattle manure treatment significantly exceeded the organic treatment. Under the mineral + cattle manure treatment, plant-available P reached 133 and 132 mg P/kg soil in the CFR and CRC crop rotations, respectively. According to the Chirikov classification, these values indicate a very

high phosphorus supply and suggest that phosphorus fertiliser rates could be reduced.

In the CFR crop rotation, exchangeable K content increased from 64 mg K/kg soil in the unfertilised treatment to 77–86 mg K/kg soil under the organic system and mineral fertilisation with straw incorporation, and to 91 mg K/kg soil under the mineral + cattle manure treatment. In the CRC crop rotation, the highest value was also recorded under the mineral + cattle manure treatment, at 86 mg K/kg soil. However, the differences among treatments were not significant, indicating only a tendency towards increased exchangeable K content.

At BBCH 29, the mineral + cattle manure treatment therefore provided the highest plant-available P content in both crop rotations, whereas the unfertilised treatments generally had the lowest values. In contrast, exchangeable K content did not differ significantly from that of the unfertilised treatment, indicating only a tendency towards higher K availability under fertilisation.

Under clover in the CFR crop rotation, mineral N content ranged from 16.1 to 19.6 mg N/kg soil,

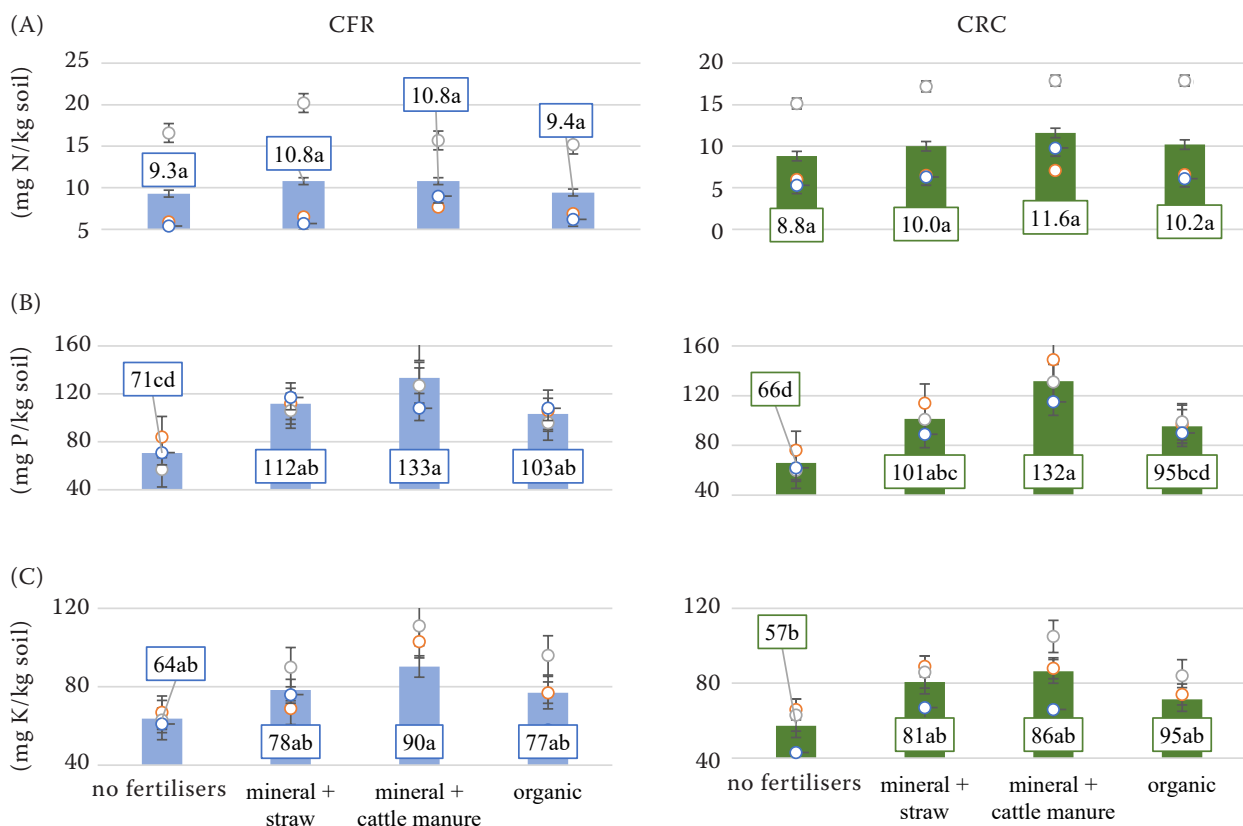


Figure 4. Contents of (A) mineral nitrogen (N); (B) plant-available phosphorus (P), and (C) exchangeable potassium (K) in soil under spring barley at growth stage BBCH 29. CFR – cereal-fodder-row crop rotation; CRC – cereal-row-crop rotation

with the highest value recorded under the mineral + cattle manure treatment (Figure 5). Under soybean in the CRC crop rotation, it ranged from 17.1 to 22.3 mg N/kg soil, with the highest value recorded under mineral fertilisation with straw incorporation. Although fertilised treatments tended to contain more mineral nitrogen than the unfertilised control, the differences were not significant.

ANOVA followed by Tukey's *HSD* test revealed significant differences in plant-available P content among fertilisation systems. The highest plant-available P content was recorded under mineral + cattle manure treatment for both clover and soybean. Compared with the unfertilised treatment, plant-available P was higher by 78 mg P/kg soil, or 120.1%, in the CFR crop rotation and by 52 mg P/kg soil, or 66.1%, in the CRC crop rotation. Under soybeans, plant-available P increased from 78 mg P/kg soil in the unfertilised treatment to 94 mg P/kg soil under the organic system, 115 mg P/kg soil under mineral fertilisation with straw incorporation, and 130 mg P/kg soil under the mineral + cattle manure treatment.

Soil OC content and stocks. In the CFR crop rotation, OC stocks were lowest in the unfertilised treatment (63.2 t C/ha) and increased to 67.9 t C/ha under the mineral + straw treatment and 67.1 t C/ha under the organic treatment; these two fertilised treatments did not differ significantly (Table 2). The highest OC stock, 70.8 t C/ha, was recorded under the mineral + cattle manure treatment and was significantly higher than under the other treatments.

In the CRC crop rotation, OC stocks were generally lower than in the CFR crop rotation. They ranged from 60.3 t C/ha in the unfertilised treatment to 63.2 t C/ha under the mineral + cattle manure treatment. The mineral + straw treatment resulted in 61.9 t C/ha, whereas the organic treatment resulted in 61.1 t C/ha and did not differ significantly from either the unfertilised or mineral + straw treatments.

Overall, the mineral + cattle manure treatment resulted in the highest OC content and OC stocks in both crop rotations: 1.98% and 70.8 t C/ha in the CFR crop rotation, and 1.77% and 63.2 t C/ha in the CRC crop rotation. The consistently higher OC values

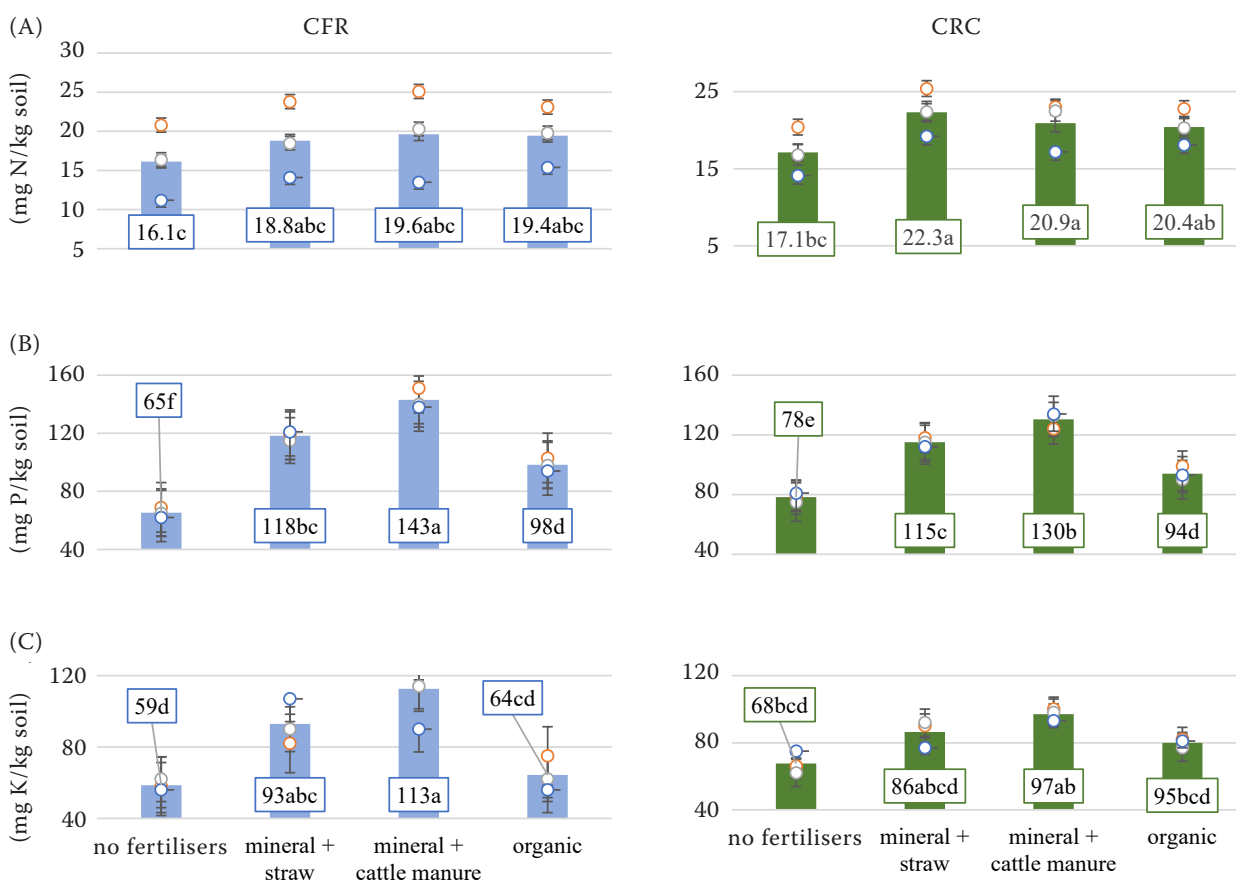


Figure 5. Contents of (A) mineral nitrogen (N); (B) plant-available phosphorus, and (C) exchangeable potassium in the 0–30 cm soil layer under clover at growth stage BBCH 50 and soybean at growth stage BBCH 29. CFR – cereal-fodder-row crop rotation; CRC – cereal-row-crop rotation

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Table 2. Soil organic carbon (OC) content and stocks under different fertilisation systems and crop rotation

Fertilisation system	Crop rotation			
	CFR:OC (%)	CFR:OC stock (t C/ha)	CRC:OC (%)	CRC:OC stock (t C/ha)
No fertilisers since 1976	1.77 ± 0.010 ^c	63.2 ± 0.55 ^c	1.69 ± 0.021 ^e	60.3 ± 0.60 ^e
Mineral fertilisers + straw	1.90 ± 0.015 ^b	67.9 ± 0.60 ^b	1.73 ± 0.006 ^d	61.9 ± 0.35 ^d
Mineral + cattle manure	1.98 ± 0.035 ^a	70.8 ± 1.15 ^a	1.77 ± 0.017 ^c	63.2 ± 0.55 ^c
Organic	1.88 ± 0.017 ^b	67.1 ± 0.35 ^b	1.71 ± 0.06 ^{de}	61.1 ± 0.35 ^{de}

Values are means ± standard deviation. Different lowercase letters indicate significant differences among crop rotation × fertilisation system combinations according to Tukey's *HSD* test at $P \leq 0.05$. Means sharing at least one letter are not significantly different. CFR – cereal-fodder-row crop rotation; CRC – cereal-row-crop rotation

in the CFR crop rotation indicate that crop rotation structure also contributed to maintaining soil organic carbon. These findings highlight the importance of combining organic and mineral fertilisers with an appropriate crop rotation for maintaining soil OC in typical Chernozem.

Crop productivity as affected by fertilisation system and crop rotation. For winter wheat, mean grain yield increased from 4.52 and 3.93 t/ha in the unfertilised treatments to 6.65 and 6.35 t/ha under the mineral + cattle manure treatment in the CFR and CRC crop rotations, respectively (Table 3). In the CFR crop rotation, the mineral + cattle manure treatment produced the highest yield (6.65 t/ha), although it did not differ significantly from the mineral + straw treatment (6.20 t/ha). In the CRC crop rotation, the mineral + straw and mineral + cattle manure treatments did not differ significantly either.

For sugar beet, the highest mean root yields were recorded under the mineral + cattle manure treatment: 46.9 t/ha in the CFR crop rotation and 42.2 t/ha in the CRC crop rotation, compared with 18.8 and 17.1 t/ha, respectively, in the unfertilised treatments. In the CFR crop rotation, the mineral + cattle manure

treatment significantly exceeded the organic and unfertilised treatments but did not differ significantly from the mineral + straw treatment. In the CRC crop rotation, the mineral + cattle manure treatment significantly exceeded the organic and unfertilised treatments, whereas the mineral + straw treatment occupied an intermediate statistical position.

Spring barley grain yield also increased under fertilisation. In the CFR crop rotation, the highest mean yield was recorded under the residual effect of the mineral + cattle manure treatment (3.74 t/ha). However, it did not differ significantly from the mineral + straw treatment (3.38 t/ha). In the CRC crop rotation, the highest yields were recorded under the mineral + straw and mineral + cattle manure treatments, at 3.86 and 3.95 t/ha, respectively, with no significant difference between them.

Overall, the unfertilised treatments generally produced the lowest crop yields, demonstrating the adverse effect of long-term cultivation without nutrient replenishment. The mineral + cattle manure treatment generally produced high numerical yields; however, in several cases, it did not differ significantly from the mineral + straw treatment. These results

Table 3. Crop yields as affected by fertilisation system and crop rotation (t/ha)

Crop	Unfertilised		Mineral + straw		Mineral + cattle manure		Organic	
	CFR	CRC	CFR	CRC	CFR	CRC	CFR	CRC
Winter wheat	4.52 ± 0.56 ^c	3.93 ± 0.22 ^c	6.20 ± 0.73 ^{ab}	6.11 ± 0.40 ^{ab}	6.65 ± 0.57 ^a	6.35 ± 0.53 ^{ab}	5.84 ± 0.62 ^b	5.84 ± 0.58 ^b
Sugar beet	18.8 ± 3.64 ^d	17.1 ± 2.16 ^d	41.7 ± 3.67 ^{ab}	38.8 ± 4.16 ^{bc}	46.9 ± 4.10 ^a	42.2 ± 3.58 ^{ab}	35.0 ± 4.32 ^c	33.8 ± 4.25 ^c
Barley	2.35 ± 0.34 ^d	2.53 ± 0.34 ^d	3.38 ± 0.09 ^{bc}	3.86 ± 0.20 ^a	3.74 ± 0.22 ^{ab}	3.95 ± 0.30 ^a	3.03 ± 0.17 ^c	3.17 ± 0.26 ^c

Values are means ± standard deviation. Different lowercase letters indicate significant differences among crop rotation × fertilisation treatment combinations according to Tukey's *HSD* test at $P \leq 0.05$. Means sharing at least one letter are not significantly different. CFR – cereal-fodder-row crop rotation; CRC – cereal-row-crop rotation

highlight the importance of combining adequate mineral nutrient supply with organic matter inputs or the return of crop residues to maintain crop productivity and soil OC in typical Chernozem.

DISCUSSION

Typical Chernozems can maintain relatively high OC levels over long periods because of their substantial organic matter reserves, deep humus-accumulative horizon, high base saturation, and capacity to form stable organo-mineral complexes. However, in the absence of fertiliser application, a negative soil nutrient balance develops, and the contents of plant-available nutrients, particularly nitrogen, phosphorus, and potassium, gradually decline. This limits plant nutrition and ultimately leads to a progressive reduction in crop productivity. Thus, high OC content determines the potential fertility of Chernozem, whereas its effective conversion into crop yield can be achieved only through balanced fertilisation and systematic nutrient replenishment.

Long-term fertilisation substantially affected soil nutrient status. Plant-available P increased under mineral, organic, and combined fertilisation, whereas the unfertilised treatments generally had the lowest values. The high and very high P contents observed in several fertilised treatments indicate that phosphorus rates should be adjusted based on soil-test results, crop nutrient removal, and the residual effects of previous fertilisation to avoid unnecessary nutrient accumulation (Mühlbachová et al. 2025, Suwara et al. 2025). Potassium appeared to be more limiting, particularly under crops with high K demand such as sugar beet, where adequate exchangeable K is essential for water relations, assimilate transport, and sugar accumulation (Füllgrabe et al. 2022).

Under spring barley, residual fertilisation effects were more evident for plant-available P and exchangeable K than for mineral N, which did not differ significantly among treatments. This may reflect rapid crop N uptake, microbial N transformations, and the strong influence of weather conditions on soil N dynamics (Hanhur et al. 2021). The generally lower nutrient availability under the unfertilised treatment underscores the importance of systematic nutrient replenishment, whereas, in some cases, the lower availability under the organic treatment may be due to slower nutrient release from manure.

The results also highlight the importance of combining organic and mineral nutrient sources. The

mineral + cattle manure treatment generally maintained the highest OC content and favourable nutrient status, reflecting the complementary effects of readily available mineral nutrients and organic matter supplied with manure. At the same time, this treatment received the highest total nutrient inputs; therefore, its performance should not be interpreted as evidence of greater nutrient-use efficiency. Mineral fertilisation with straw incorporation also improved soil nutrient status and, in several cases, approached the performance of manure-based treatment, indicating that systematic crop residue return can partly compensate for limited manure availability.

Crop productivity was strongly influenced by fertilisation, although the magnitude of the response differed among crops and crop rotations. The lowest yields were consistently recorded in the unfertilised treatments, confirming that the inherent nutrient reserves of typical Chernozem were insufficient to sustain high productivity after prolonged cultivation. Similar patterns have been reported in other long-term experiments, where mineral, organic, and combined fertilisation increased nutrient availability and crop yields (Černý et al. 2010, Ludwig et al. 2011, Giacometti et al. 2021).

The combined mineral + cattle manure treatment supported high crop productivity due to the complementary supply of mineral nutrients and organic matter. Still, its effect should be interpreted in relation to the higher nutrient inputs applied. Similar long-term studies have shown that combined manure and mineral fertilisation can support balanced nutrient supply and high sugar beet productivity compared with organic fertilisation alone (Hlisenikovsky et al. 2021, Barłóg and Grzebisz 2025, Barłóg et al. 2025). Mineral fertilisation with straw incorporation also produced high yields, particularly for sugar beet and barley, indicating that the return of crop residues can partly substitute for manure where its availability is limited.

Crop rotation further modified fertiliser effects. Sugar beet yields were slightly higher in the CFR crop rotation, probably because of the inclusion of clover and a more diversified crop sequence. Legumes contribute biologically fixed N and root residues, improve soil structure, and may enhance nutrient cycling and yield stability (Giacometti et al. 2021, Suwara et al. 2025). The effect of fertilisation also depended on weather conditions, crop characteristics, and nutrient demand, which explains why increasing nutrient inputs did not always result in

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proportional increases in soil nutrient availability or yield (Hijbeek et al. 2017).

Overall, long-term crop productivity in typical Chernozem was determined by the interaction among fertilisation, crop biological characteristics, rotation structure, and annual weather conditions. The mineral + cattle manure treatment generally supported high crop productivity by combining a readily available mineral nutrient supply with the longer-term soil-improving effects of organic matter. However, the high productivity achieved under mineral fertilisation with straw incorporation confirms that systematic return of crop residues can partly replace manure as a source of organic matter. These findings support crop-specific and rotation-specific fertilisation strategies rather than uniform fertiliser recommendations for the entire crop sequence.

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