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Effects of treatment systems on carbon dioxide emissions and the agrochemical state of chernozems

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Abstract

Background and Aim. Organic carbon dynamics and carbon dioxide (CO_2) emissions of soil are important indicators of soil functioning and the sustainability of agricultural systems. In Northern Kazakhstan, intensive soil cultivation and contrasting climatic conditions may influence the mineralization of soil organic matter and soil nutrient availability. Conservation tillage practices, including no-till, may contribute to maintaining carbon in soil and soil fertility; however, their effects on CO_2 emissions and agrochemical properties of ordinary chernozem under regional conditions remain studied insufficiently. To evaluate the effects of soil tillage systems and mineral fertilization on the intensity of carbon dioxide (CO_2) emissions and agrochemical properties of ordinary chernozem under the conditions of Northern Kazakhstan.

Materials and Methods. Field experiments were conducted during 2024–2025 at the Karabalyk Agricultural Experimental Station on ordinary chernozem soil. Conventional tillage and no-till systems, as well as fallow treatment, were analyzed under unfertilized (control) and mineral fertilizer (N30P20) conditions. The intensity of CO_2 emissions of the soil was determined at the main growth stages of spring wheat. Humus content, nitrate nitrogen (N-NO_3), available phosphorus (P_2O_5), and exchangeable potassium (K_2O) were also determined.

Results. The intensity of soil CO_2 emissions depended on the tillage system and mineral fertilization. The highest CO_2 emission was recorded at the tillering stage, reaching 25.0 g CO_2 /m-2 under conventional tillage with the use of mineral fertilizer. By the end of the growing season, CO_2 emissions decreased to 2.1-4.1 g CO_2/m-2. Higher temperatures in 2025 enhanced organic matter mineralization and stimulated carbon cycling. Compared to conventional tillage, the no-till system maintained more stable humus content and mineral nutrient levels.

Conclusion. The no-till system combined with mineral fertilization contributes to the preservation of soil fertility and the stabilization of the soil carbon regime, thereby improving the efficiency of sustainable farming systems under the Northern Kazakhstan conditions.

Keywords: no-till; soil; mineral fertilizers; carbon dioxide emissions; humus; soil agrochemical properties.

Introduction

Located at the interface of the atmosphere, lithosphere, and biosphere, soil plays a pivotal role in the biogeochemical cycling of CO_2 and other gases [1]. It is the principal reservoir of organic carbon and serves as one of the major sinks for atmospheric CO_2 through carbon sequestration. Soil carbon sequestration is recognized as an important scientific and technological approach for mitigating accumulation of atmospheric carbon dioxide. The amount of carbon stored in soils (approximately 1400–1500 Gt C) is about twice the amount contained in the atmosphere [2]. Carbon is accumulated

in the soil through photosynthesis, during which atmospheric CO_2 is absorbed by plant leaves and subsequently incorporated into soil organic matter [3, 4, 5]. According to some researchers, approximately 25–40% of atmospheric carbon dioxide emissions originate from soil respiration [6].

In the global cycle carbon continuously moves between the soil and the atmosphere. According to numerous studies, annual carbon emissions from soils to the atmosphere in the form of carbon dioxide are estimated at 50–77 Gt C per year [6, 7]. The flax of carbon dioxide from the soil is primarily driven by the respiration of soil microorganisms, plant roots, and soil fauna [8]. Soil respiration constitutes a major component of carbon dioxide release from soils and includes root respiration, respiration of soil fauna, and the microbial decomposition of organic matter. It is influenced by numerous abiotic factors, such as soil temperature and moisture, as well as biotic factors, including the diversity and productivity of soil organisms [5, 9].

Agricultural use of soils significantly alters the carbon cycle and increases the concentration of carbon dioxide in the atmosphere. Soil cultivation, particularly plowing, intensifies greenhouse gas emissions from chernozem soils, resulting in a reduction of soil carbon stocks by 30–50% of their original content over the past 50 years. Carbon emissions to the atmosphere resulting from such soil transformation have been estimated at approximately 1,14 ± 0,18 Gt C per year [8, 10]. In addition, carbon dioxide emissions from agricultural soils vary, depending on the intensity of land use and the interaction with the weather conditions. These emissions are determined by the specific characteristics of the soil cover, agricultural practices, cultivation technologies, plant species composition, vegetation density, and the physiological state of plants.

The primary factor influencing changes in carbon dioxide (CO_2) emissions is the tillage system. Conservation tillage promotes the preservation of soil organic carbon by reducing soil aeration and slowing the mineralization of organic residues. No-till is considered one of the most effective practices for increasing carbon sequestration from the atmosphere into plants and soil due to lower CO_2 emissions [11]. Under this system, the soil structure and surface layer remain undisturbed, while CO_2 is kept or sequestrated through crop residues, root system, and soil microbial processes. In addition, no-till helps mitigate both wind and water erosion [12, 13]. In contrast, conventional tillage leads to a decline in soil humus content, deterioration of soil structure, increased soil aeration, and accelerated decomposition of organic matter, resulting in higher carbon dioxide emissions from the soil [14, 15].

Plant mineral nutrition, particularly nitrogen fertilization, is one of the key factors regulating the carbon cycle. The application of nitrogen fertilizers influences soil processes by stimulating plant growing and development, increasing crop productivity, and enhancing both biological activity and the mineralization of organic matter. This phenomenon is known as the “priming effect”, whereby the addition of mineral nitrogen accelerates the decomposition of soil organic carbon, leading to increased carbon dioxide emissions from the soil.

According to *Cherkasov* et al., carbon losses and CO_2 emissions from soils under different environmental and management conditions remain studied insufficiently [16].

Purpose of the study: to determine the effects of soil tillage systems and mineral nutrition on CO_2 emissions, organic matter transformation, and the agrochemical status of ordinary chernozem in Northern Kazakhstan.

Research objectives: to investigate the seasonal dynamics of CO_2 emissions under different soil tillage systems; to determine changes in humus content, soil organic carbon, and its fractional composition; to access the dynamics of the main soil agrochemical properties, including nitrate nitrogen ($N\text{-}NO_3$), available phosphorus (P_2O_5) and exchangeable potassium (K_2O); to evaluate the effects of mineral fertilization and weather conditions on the mineralization of soil organic matter; to substantiate the effectiveness of conservation farming practices in regulating the soil carbon regime and maintaining the fertility of ordinary chernozem soils.

Materials and Methods

The study was conducted on ordinary chernozem soils located in the steppe zone at Karabalyk Agricultural Experimental Station LLP Karabalyk district, Kostanay region, Kazakhstan.

The field experiment was established on an agricultural landscape represented by medium-depth ordinary chernozem soils formed under the conditions of a temperate continental climate during 2024–2025 at the Karabalyk agricultural experimental station, Nauchny settlement, Karabalyk district,

Kostanay region. Experimental plots were established according to the experimental design, including conventional tillage and no-till systems.

The experiment comprised control plots (without fertilizer application) and plots treated with nitrogen and phosphorus fertilizers at a rate of N30P20. A fallow treatment without mineral fertilizer application was also included in the experimental design. Each experimental plot measured 52 × 6 m (0.0312 ha) and the total experimental area was 0.2 ha (Table 1). Sowing and fertilizer application were carried out during the first ten days of May using spring wheat as the test crop. Ammophos and ammonium nitrate were applied to the fertilized plots at a rate of N30P20.

Table 1. Experimental design

Conventional tillage Control (without fertilizer application)	Conventional tillage Ammonium nitrate (N30), ammophos (P20)	No-till Control (without fertilizer application)	No-till Ammonium nitrate (N30), ammophos (P20)	Fallow plot

To assess soil fertility prior to establishing the field experiment, a soil profile was excavated on a watershed site and soil samples were collected from each genetic horizon for laboratory analysis. The soil profile exhibited weak differentiation between horizons, while a distinct boundary based on color was observed between the plow layer and the B_1 horizon. The combined thickness of the humus horizons (A + B_1) was 46 cm, classifying the soil as medium-platy structure in the Ap and B_1 horizons, gradually changing to a platy structure in the B2 and BC horizons. Soil bulk density increased with depth, ranging from loose in the upper horizons to dense in the lower part of the profile. Strong effervescence with 10% hydrochloric acid (HCl) was observed from a depth of 45 cm, indicating the presence of carbonates. Carbonate accumulations in the form of impregnations were identified in the BC horizon.

Ordinary chernozem with a humus content exceeding 4% is classified as low-humus soil, indicating a moderate level of fertility and certain limitations in the accumulation of soil organic matter. The heavy loam texture developed on loess-like loam provides high water-holding capacity and considerable buffering capacity, contributing to the resilience of the agricultural landscape under drought conditions.

The experiment was conducted throughout the growing season from May to September and CO_2 emissions were measured using Shtanov's method [17].

According to the experimental design, soil samples were collected during the growing season from each treatment in three replicates for the analysis of the chemical, agrophysical and physicochemical properties of the soil under different agricultural management practices and analyzed using standard analytical procedures. Nitrate nitrogen (N-NO_3) was determined by the ionometric method, available phosphorus (P_2O_5) and exchangeable potassium (K_2O) by the Machigin method, humus by the Tyurin method, total nitrogen by the Kjeldahl method and soil organic carbon together with its fractions (labile carbon, humic acid carbon, and fulvic acid carbon) using conventional methods for soil organic matter fractionation [18]. All analytical determinations were performed in accordance with the relevant interstate State Standards (GOST) adopted and applied in the Republic of Kazakhstan. The experimental data were processed using descriptive statistical methods. Analysis of variance (ANOVA) was applied to evaluate the effects of soil tillage systems and mineral fertilization on the studied parameters and differences between treatment means were considered statistically significant at $p < 0.05$.

Results

Meteorological conditions during 2024–2025 were characterized by significant deviations from the long-term average. In 2024, the mean annual air temperature was +3.8 ºC, increasing to +5.8 ºC in 2025, compared to the long-term average of +2.9 ºC. These data indicate warmer than average conditions during the study period, particularly in the spring of 2025. The highest air temperatures were recorded in June and July (19.4–20.7 ºC), which promoted the intensification of biological processes in the soil (Figure 1).

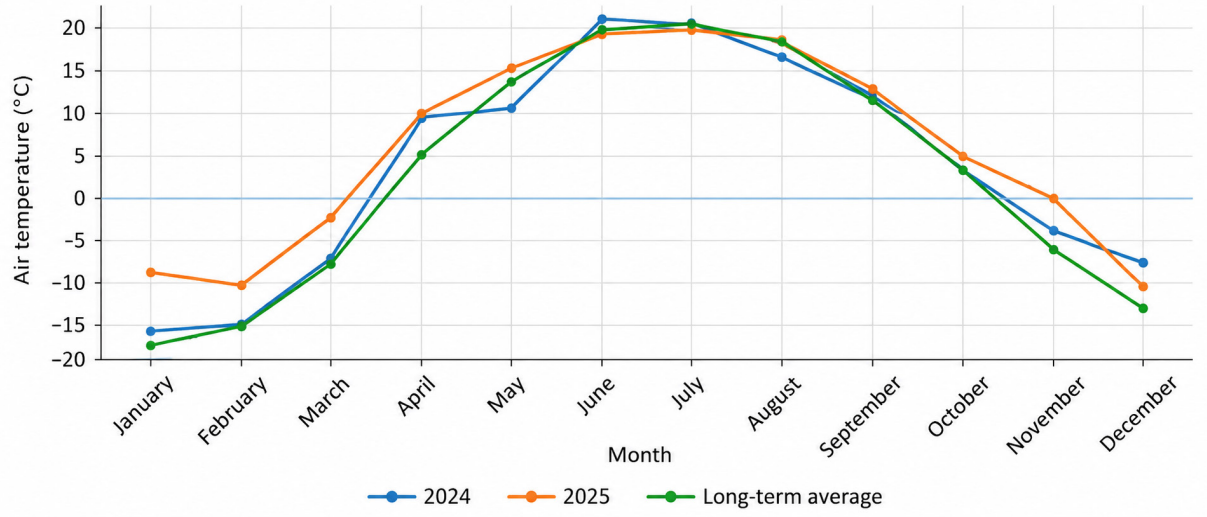


Figure 1. Average monthly air temperature in 2024–2025 and the long-term average at the Karabalyk Agricultural Experimental Station

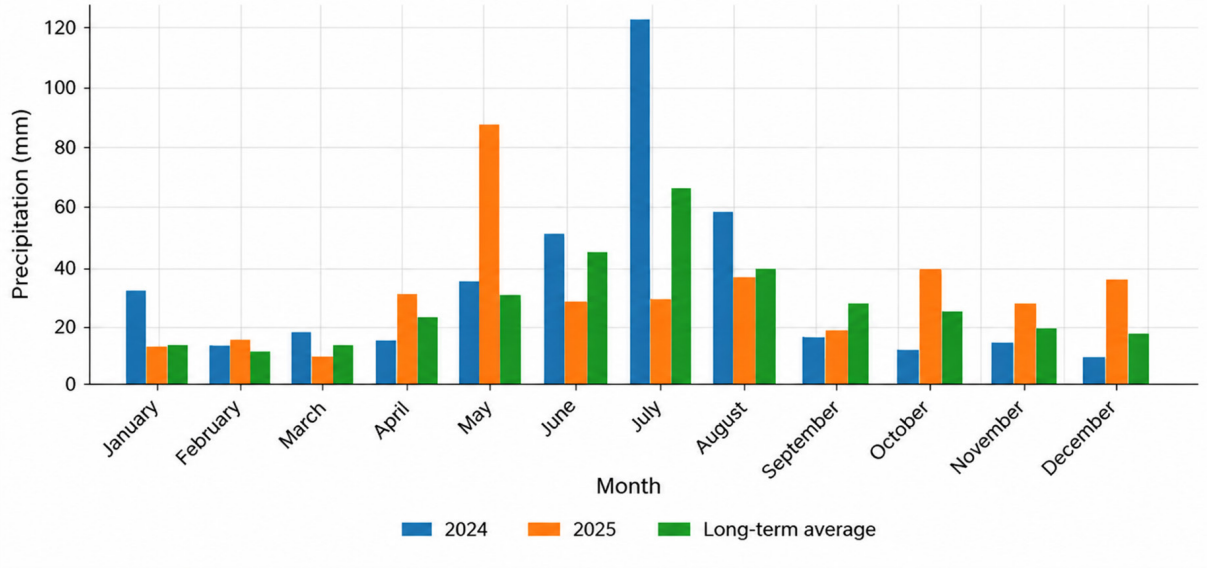


Figure 2. Monthly precipitation distribution in 2024–2025 and the long-term average at the Karabalyk Agricultural Experimental Station

Precipitation distribution varied considerably between the study years. In 2024, total precipitation during the growing season reached 269 mm, substantially exceeding the long-term average of 184 mm. The highest monthly precipitation was recorded in July (122 mm). By contrast, the 2025 growing season was characterized by relatively dry conditions with a total precipitation of 183 mm, despite increased rainfall in May (87 mm). Thus, 2024 was characterized by above-average moisture availability, whereas 2025 was warmer and relatively drier. Hydrothermal conditions differed considerably between the study years. In 2024, the Hydro-thermal Coefficient of Selyaninov (HTC) was 1.0 in June, 1.8 in July, and 1.0 in August, indicating generally sufficient moisture availability during the main part of the growing season, with particularly high moisture availability in July. By contrast, the hydrothermal regime of 2025 was markedly more variable. The HTC was 1.9 in May, indicating high moisture availability at the beginning of the growing season, but subsequently decreased to 0.8 in June, 0.4 in July, and 0.7 in August. According to the Selyaninov classification, these values indicate the development of increasingly arid conditions during the summer, with the most pronounced moisture deficit occurring in July. Thus, 2024 was characterized by generally more favorable moisture conditions, whereas 2025 had a contrasting hydrothermal regime, with a moist beginning of the growing season followed by relatively dry conditions during June-August. These contrasting meteorological conditions had a significant influence on the intensity of soil biological processes and CO_2 emissions from the soil.

Table 2. Changes in the humus content of ordinary chernozem under different soil tillage systems and fertilization treatments in 2024–2025, %

Tillage system	Treatment	Before sowing		Tillering stage		Heading stage		After harvest	
		2024	2025	2024	2025	2024	2025	2024	2025
Conventional	Control	4.18	4.40	4.18	4.41	4.30	4.36	4.24	4.34
	N30P20	4.52	4.60	4.50	4.58	4.60	4.61	4.18	4.60
No-till	Control	4.78	4.55	4.77	4.54	4.65	4.52	4.58	4.57
	N30P20	4.60	4.68	4.65	4.70	4.68	4.71	4.79	4.65
Fallow		4.50	4.41	4.56	4.37	4.59	4.59	4.60	4.35

According to the analytical results, the ordinary chernozem soils contained 4.18–4.79% humus and were classified as low-humus soils. Changes in soil humus content during 2024–2025 were influenced by the soil tillage system, mineral fertilization, and the growth stages of spring wheat (Table 2).

The climatic conditions of 2025 were characterized by a warmer spring and a less uniform distribution of precipitation than in 2024, which accelerated soil biochemical processes and enhanced the decomposition of soil organic matter. Under the no-till control treatment, humus content decreased compared with 2024, from 4.78% to 4.55% before sowing and from 4.77% to 4.54% at the tillering stage. This decline was associated with intensified organic matter mineralization resulting from higher temperatures, increased microbial activity and limited soil moisture availability.

Data analysis showed that in the unfertilized control treatments, humus content was lower and tended to decline by the end of the growing season.

Under conventional tillage, changes in humus content were less distinct. During the early growth stages in 2025, the control treatment showed a slight increase in humus content (4.40–4.41%), followed by stabilization at 4.30–4.34% during the remainder of the growing season. In contrast, the treatment receiving mineral fertilizers (N30P20) exhibited more stable humus preservation and a partial increase, reaching 4.60% by the end of the growing season. This improvement was associated with enhanced plant growth and biomass production, resulting in greater inputs of plant residues that partially compensated for the loss of soil organic matter.

The no-till system was characterized by higher humus content and greater preservation of soil organic carbon, which can be attributed to reduced soil disturbance and slower decomposition of organic matter. However, in 2025, a slight decline in humus content was observed during the early growth stages of the crop. Mineral fertilizer application promoted an increase in humus content by enhancing soil biological productivity and increasing the input of plant residues. The accumulation of humus depends on the amount of plant residue returned to the soil, its decomposition rate, the soil's capacity to stabilize humic substances, and the rate of humus mineralization [19]. In the present study, mineral fertilization resulted in relatively high humus contents (4.65–4.71%), indicating the potential to maintain stable humus levels through reduced mechanical soil disturbance and increased accumulation of plant residues. These findings are consistent with the previous studies [19, 20], which reported the positive effects of no-till practices and mineral fertilization on the preservation and accumulation of soil organic matter.

A consistent decline in soil humus content during the growing season was observed in the fallow treatment in 2025 compared with 2024. This decrease was associated with the absence of fresh organic matter inputs and the intensified mineralization of soil organic carbon.

Nitrate nitrogen ($N\text{-}NO_3$), one of the most readily available forms of nitrogen for plants, plays a key role in plant nutrition and crop productivity. The concentration of soil $N\text{-}NO_3$ is influenced by agronomic practices, particularly soil tillage systems and fertilization regimes. Evaluating the seasonal dynamics of soil $N\text{-}NO_3$ provides valuable information for optimizing crop management practices and improving nitrogen use efficiency.

The agrochemical analysis of ordinary chernozem showed very low, low, and moderate levels of nitrate nitrogen in the topsoil during 2024–2025. The $N\text{-}NO_3$ content ranged from 2.8 to 11.0 mg kg^{-1}, indicating the high mobility of mineral nitrogen in the soil under agricultural conditions (Table 3).

Table 3. Dynamics of soil nitrate nitrogen (N-NO_3) content under different tillage systems and fertilization treatments during 2024–2025, mg kg^{-1}

Tillage system	Treatment	Before sowing		Tillering stage		Heading stage		After harvest	
		2024	2025	2024	2025	2024	2025	2024	2025
Conventional	Control	10.8	10.5	9.5	6.9	11.0	4.6	5.5	2.8
	N30P20	7.9	7.4	6.9	6.8	10.4	6.4	8.3	3.4
No-till	Control	8.5	8.0	8.0	8.2	8.5	6.4	6.6	3.4
	N30P20	9.2	8.7	11.0	10.7	6.8	6.5	7.6	3.1
Fallow		7.5	7.2	9.9	9.9	7.0	7.0	7.6	7.6

The 2025 growing season was characterized by a warmer spring and a less uniform distribution of precipitation than 2024, which contributed to a decline in soil nitrate nitrogen (N-NO_3) content during the second half of the growing season.

Under the conventional tillage system, the control treatment showed relatively high nitrate nitrogen (N-NO_3) content before sowing, with only minor differences between years (10.8–10.5 mg kg^{-1}). However, at the tillering stage, the N-NO_3 content decreased to 6.9 mg kg-1 in 2025 compared with 9.5 mg kg-1 in 2024, indicating more intensive nitrogen uptake by plants and faster depletion of mineral nitrogen under higher temperatures. At the heading stage, the differences between years became even more pronounced. In 2024, the N-NO_3 content reached 11.0 mg kg^{-1}, whereas in 2025 it declined to 4.6 mg kg^{-1}. After harvest, nitrate nitrogen content remained lower in 2025, reflecting the overall depletion of available nitrogen by the end of the growing season. A similar trend was observed in the fertilized treatment under conventional tillage. Compared with 2024, nitrate nitrogen content in 2025 decreased during the heading stage and after harvest. This reduction can be attributed to increased nitrogen uptake by plants for biomass production and grain formation, as well as the possible leaching of nitrate nitrogen into deeper soil horizons.

Under the no-till system, the seasonal dynamics of soil nitrate nitrogen (N-NO_3) were more stable, reflecting the preservation of crop residues and a more balanced mineralization regime. In the unfertilized control treatment, N-NO_3 concentrations remained relatively stable during the first half of the growing season and gradually declined toward harvest, indicating a more gradual release of nitrogen from soil organic matter. In the fertilized treatment, nitrate nitrogen accumulated to its highest levels at the tillering stage (11.0 mg kg^{-1} in 2024 and 10.7 mg kg^{-1} in 2025), reflecting the combined effect of fertilizer-derived mineral nitrogen and enhanced nitrification under the warmer spring conditions. During the subsequent growth stages, N-NO_3 concentrations declined to 6.5-7.6 mg kg^{-1}, primarily due to active nitrogen uptake by the growing plants.

The fallow treatment was characterized by relatively high nitrate nitrogen (N-NO_3) availability in both study years, which can be attributed to the absence of cultivated plants and the accumulation of mineral nitrogen through the mineralization of soil organic matter. During the growing season, however, N-NO_3 concentrations showed a gradual stabilization followed by a decline, reflecting natural nitrogen losses and a reduction in the intensity of soil microbial activity [20].

Phosphorus is one of the essential macronutrients determining crop productivity. Its plant-available form (P_2O_5) plays a crucial role in energy transfer, root development and yield formation. The availability of phosphorus in soil is strongly influenced by tillage practices, fertilization regimes and the biological characteristics of the cultivated crop.

The availability of plant-accessible phosphorus in the ordinary chernozem soils ranged from moderate to high throughout the growing season. This seasonal variation was determined by a combination of interacting factors, including the activation of soil microbial processes under warm and moist conditions, which promoted the mineralization of organic matter and the release of plant-available phosphorus. In addition, the application of phosphorus fertilizers directly increased the concentration of available phosphorus, while changes in soil physicochemical properties, particularly moisture and temperature, influenced phosphorus solubility and mobility.

The climatic conditions of the study years had a significant influence on the availability of plant-accessible phosphorus. The higher precipitation recorded in 2024 may have influenced phosphorus

availability within the studied soil layer through changes in soil moisture conditions, phosphate diffusion, root activity, and plant phosphorus uptake. In 2025, the lower P_2O_5 concentrations observed in some treatments were more likely associated with the combined effects of crop phosphorus uptake, fertilizer application, and changes in the proportion of extractable phosphorus within the soil, rather than with enhanced organic matter mineralization (Table 4).

In the control treatment under conventional tillage, the content of plant-available phosphorus was generally lower throughout the 2025 growing season than in 2024. At the heading stage, P_2O_5 content increased to 28.4 mg kg^{-1} in 2025 compared with 20.0 mg kg^{-1} in 2024. This variation may reflect temporal differences in plant phosphorus uptake and the amount of extractable phosphorus within the studied soil layer. In the fertilized treatment, the accessibility of plant-available phosphorus was consistently higher than in the control. Nevertheless, lower phosphorus concentrations were observed during the early growth stages in 2025 compared with 2024 (31.8 vs. 43.1 mg kg^{-1} before sowing). At the heading stage and after harvest, P_2O_5 concentrations were 38.2 and 40.5 mg kg^{-1}, respectively, indicating temporal variation in plant-available phosphorus during the growing season (Table 4).

Table 4. Plant-available phosphorus (P_2O_5) content in soil under different tillage systems and fertilization treatments during 2024–2025, mg kg^{-1}

Tillage system	Treatment	Before sowing		Tillering stage		Heading stage		After harvest	
		2024	2025	2024	2025	2024	2025	2024	2025
Conventional	Control	38.5	33.6	40.9	32.1	20.0	28.4	31.1	27.5
	N30P20	43.1	31.8	46.0	40.0	20.9	38.2	39.7	40.5
No-till	Control	38.0	30.1	36.3	30.6	35.8	30.3	39.9	30.5
	N30P20	47.1	35.8	47.0	46.5	36.9	39.1	41.4	42.2
Fallow		48.1	30.4	54.7	54.7	23.2	23.2	45.4	45.4

The no-till system was characterized by a more stable phosphorus regime and smaller year-to-year fluctuations. In the unfertilized control treatment, plant-available phosphorus content was lower in 2025 than in 2024 at all crop growth stages. However, the seasonal pattern remained relatively stable, ranging from 30.1 to 30.6 mg kg^{-1} during the early growth stages and remaining close to 30.5 mg kg^{-1} after harvest. This stability can be attributed to minimal soil disturbance and a more uniform distribution of phosphorus within the soil-plant system.

Under the no-till system, mineral fertilization generally maintained higher levels of plant-available phosphorus compared with the unfertilized control. In the N30P20 treatment, P_2O_5 concentrations in 2024 were 47.1 mg kg^{-1} before sowing, 47.0 mg kg^{-1} at tillering, 36.9 mg kg^{-1} at heading, and 41.4 mg kg^{-1} after harvest. In 2025, the corresponding values were 35.8, 46.5, 39.1, and 42.2 mg kg^{-1}. The seasonal changes were moderate and did not indicate a consistent accumulation of plant-available phosphorus during the growing season. The observed variation likely reflected the combined effects of phosphorus fertilization, crop uptake, and temporal variability in the extractable phosphorus pool within the studied soil layer.

In the fallow treatment, a high initial level of plant-available phosphorus was observed, however, in 2025, the concentration before sowing decreased to 30.4 mg kg^{-1}, compared with 48.1 mg kg^{-1} in 2024. Throughout the growing season, phosphorus levels remained relatively stable, which can be attributed to the absence of crop uptake and, consequently, the lack of phosphorus removal with the harvested biomass.

Potassium is an essential plant macronutrient that plays a key role in numerous physiological and biochemical processes, including photosynthesis, carbohydrate synthesis and nutrient transport. It also enhances plant tolerance to drought stress and diseases. The content of plant-available potassium in soil depends on soil texture, tillage practices, and the level of fertilizer application.

The results of the agrochemical analysis showed that the ordinary chernozem soil contained very high levels of exchangeable potassium, exceeding 700 mg kg^{-1}.

A comparison of the two study years demonstrated that exchangeable potassium concentrations in 2025 were generally lower than in 2024 across all treatments. This decline may be attributed to the

warmer growing season and the uneven distribution of precipitation, which likely enhanced potassium uptake by plants and promoted its migration into deeper soil horizons (Table 5).

Table 5. Exchangeable potassium (K_2O) content in soil under different tillage systems and fertilization treatments during 2024–2025, mg kg^{-1}

Tillage system	Treatment	Tillering stage		Heading stage		After harvest	
		2024	2025	2024	2025	2024	2025
Conventional	Control	734	715	854	731	860	722
	N30P20	882	730	876	727	860	730
No-till	Control	743	735	822	748	1023	727
	N30P20	784	750	815	736	1171	740
Fallow		739	739	910	910	1005	1005

Under the conventional tillage system, the unfertilized control treatment exhibited a consistent decline in exchangeable potassium content in 2025 compared with 2024. At the tillering stage, potassium concentrations decreased from 734 to 715 mg kg^{-1}, at the heading stage from 854 to 731 mg kg^{-1} and after harvest from 860 to 722 mg kg^{-1}. A similar seasonal pattern was observed in the fertilized treatment under conventional tillage, where exchangeable potassium concentrations were also lower in 2025 than in the previous year.

Under the no-till system, exchangeable potassium concentrations were higher in 2024, particularly after harvest, when values reached 1023–1171 mg kg^{-1}. This accumulation may be attributed to the retention of potassium in the topsoil due to the absence of mechanical soil disturbance and the preservation of crop residues. In 2025, exchangeable potassium content declined to 736–750 mg kg^{-1}, reflecting more intensive potassium uptake by plants under conditions of enhanced crop growth and higher temperatures.

The fallow treatment exhibited relatively stable exchangeable potassium concentrations (739–1005 vu kg^{-1}), which can be attributed to the absence of potassium removal by harvested crops.

The obtained results demonstrated that soil carbon dioxide (CO_2) emissions varied depending on the tillage system, mineral fertilization regime and the climatic conditions during the 2024–2025 growing seasons (Figure 3 and 4).

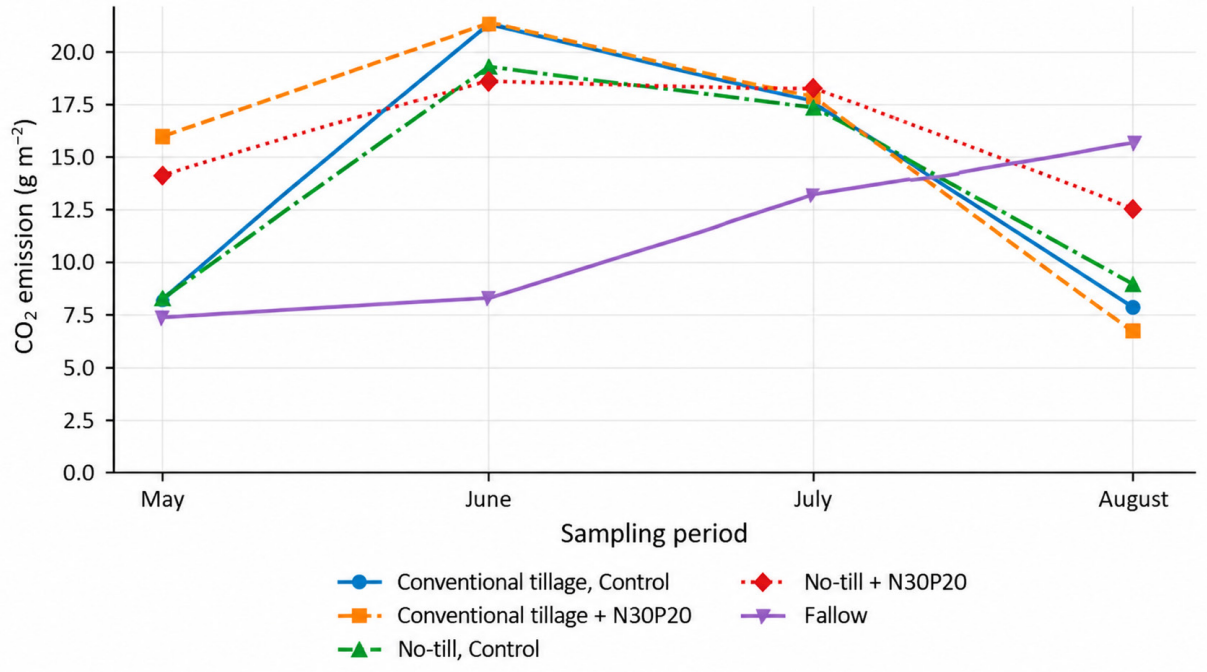


Figure 3. Seasonal dynamics of soil CO_2 emissions under different tillage systems and mineral fertilization levels in 2024

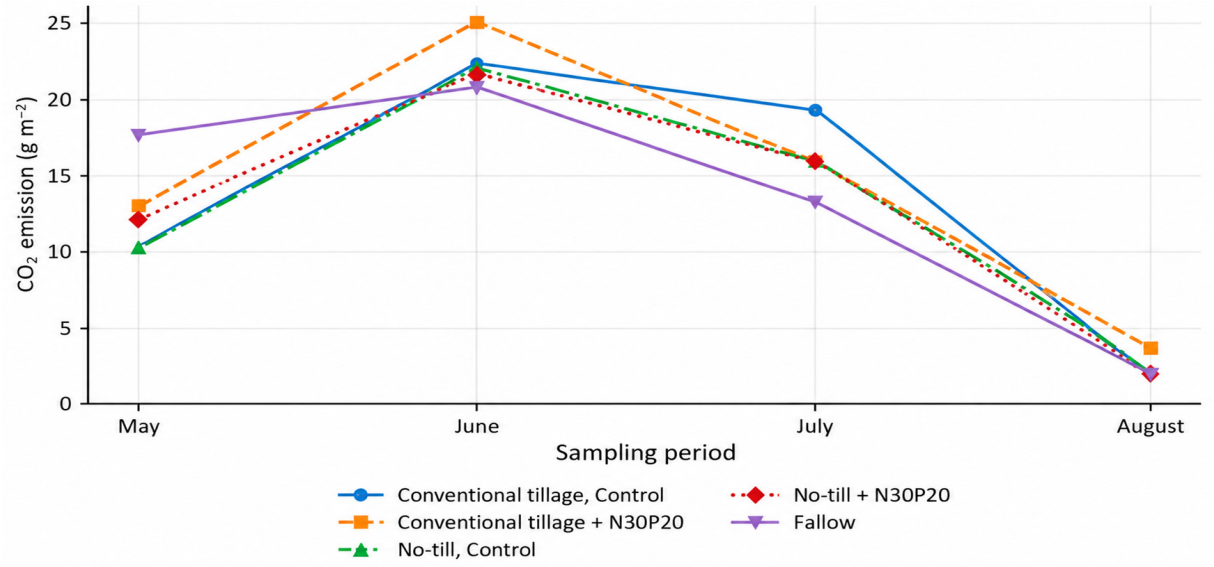


Figure 4. Seasonal dynamics of soil CO_2 emissions under different tillage systems and mineral fertilization levels in 2025

During the early growth stages of spring wheat (May–June), soil CO_2 emissions were higher in 2025 than in 2024. In May, CO2 emissions in the unfertilized control treatments increased from 7.3–8.0 to 10.1–17.5 g CO_2 m^{-2} under both conventional and no-till systems. The fallow treatment exhibited even greater CO_2 emissions, which can be attributed to the absence of vegetation cover, promoting more intensive mineralization of soil organic matter. Maximum CO_2 emissions were recorded in June, increasing from 8.1-21.4 g CO_2 m^{-2} in 2024 to 20.7-25.0 g CO_2 m^{-2} in 2025. The highest value (25.0 g CO_2 m^{-2}) was observed under conventional tillage with mineral fertilizer application, reflecting enhanced microbial activity stimulated by fertilizer inputs.

In July, the seasonal pattern of CO_2 emissions varied among the treatments. In several treatments, CO_2 emissions were lower in 2025 than in 2024, which may be associated with less favorable hydrothermal conditions and increased nitrogen uptake by plants. By contrast, annual differences in the fallow treatment were minimal, with CO_2 emissions of 13.1 and 13.2 g CO2 m^{-2} in 2024 and 2025, respectively.

The lowest soil CO_2 emissions during the growing season were recorded in August across all treatments, particularly in 2025, when values ranged from 2.2 to 3.6 g CO_2 m^{-2}. This decline indicates the depletion of readily available soil organic carbon, reduced microbial activity and the completion of the active crop growth period toward the end of the growing season.

During the growing season, the conventional tillage system was associated with elevated soil CO_2 emissions during the early stages of spring wheat growth, reaching 10.1, 22.2 and 19.2 g CO_2 m^{-2}. In the fertilized treatment, CO_2 emissions peaked at 25.0 g CO_2 m^{-2}, indicating that nitrogen application stimulated microbial decomposition of soil organic matter. However, mineral fertilization had little effect on CO_2 emissions during the subsequent crop growth stages. The decline in CO_2 emissions toward the end of the growing season was likely related to reduced precipitation, which limited soil microbial activity. Under the no-till system, both the unfertilized and fertilized treatments exhibited a more stable pattern of soil carbon flux during the initial stages of crop development in 2024–2025. In the unfertilized treatment, CO_2 emissions ranged from 8.1 to 19.3 g CO_2 m^{-2} in 2024 and from 10.1 to 21.9 g CO_2 m^{-2} in 2025. In the fertilized treatment, the corresponding values ranged from 14.1 to 18.6 g CO_2 m^{-2} in 2024 and from 11.9 to 21.5 g CO_2 m^{-2} in 2025. Thereafter, CO_2 emissions gradually declined as the crop progressed through later developmental stages. The fallow treatment exhibited a less stable pattern of soil CO_2 emissions, characterized by high initial emission rates followed by a marked decline during the remainder of the growing season. This pattern can be attributed to the rapid depletion of soil organic carbon and the absence of fresh organic matter inputs into the soil.

The results obtained for 2024–2025 showed that soil organic carbon content ranged from 2.42 to 2.78% in 2024 but declined to 1.86–2.37% in 2025. This reduction may be attributed to a more intensive

mineralization of soil organic matter under the influence of climatic conditions and increased soil biological activity. The highest organic carbon contents were recorded in the N30P20 treatment under the no-till system, reaching 2.78 in 2024 and 2.37% in 2025. These findings indicate that conservation tillage combined with mineral fertilization promotes the accumulation and preservation of soil organic matter (Table 6).

Table 6. Changes in soil organic carbon, its fractional composition and total nitrogen in ordinary chernozem under different tillage systems and fertilization treatments during 2024–2025

Tillage system	Treatment	N total, %		SOC, %		Labile carbon, %		Humic acids (HA), %		Fulvic acids (FA), %	
		2024	2025	2024	2025	2024	2025	2024	2025	2024	2025
Conventional	Control	0.25	0.23	2.46	2.19	1.06	0.82	0.49	0.70	0.57	0.11
	N30P20	0.24	0.28	2.42	1.91	1.14	0.81	0.75	0.56	0.39	0.26
No-till	Control	0.24	0.30	2.66	1.86	0.99	0.85	0.60	0.51	0.38	0.34
	N30P20	0.27	0.25	2.78	2.37	1.19	0.90	0.67	0.53	0.52	0.36
Fallow	-	0.26	0.27	2.67	2.21	1.24	0.94	0.87	0.59	0.37	0.35

Total nitrogen is an important component of soil organic matter and its concentration reflects the status of soil humus. Total nitrogen content ranged from 0.24 to 0.27% in 2024 and from 0.23 to 0.30% in 2025, indicating high to very high nitrogen availability in the ordinary chernozem. The highest total nitrogen contents were recorded under the no-till system, suggesting better preservation of nitrogen-containing organic compounds and a more stable soil organic matter pool.

Labile carbon, the most mobile and readily decomposable fraction of soil organic matter, ranged from 0.99 to 1.24% in 2024 and from 0.81 to 0.94% in 2025. The decline in labile carbon content during the second year of the study indicates intensified mineralization of soil organic matter and greater involvement of carbon in the biogeochemical cycle. The highest labile carbon contents were recorded in the fallow treatment and in the fertilized no-till treatment.

The composition of soil humus was evaluated based on the ratio of humic acids to fulvic acids. The analysis of humus fractions showed that the content of humic acids exceeded that of fulvic acids in most treatments. In 2024, humic acid content ranged from 0.49 to 0.87%, while fulvic acid content varied from 0.37 to 0.57%. In 2025, the corresponding ranges were 0.51–0.70% and 0.11–0.36%, respectively. The predominance of humic acids indicates a more stable humus composition, whereas a higher proportion of fulvic acids reflects increased mineralization of soil organic matter. Over the two-year study period, humic acids predominated over fulvic acids in most treatments, indicating the formation of a humate-type humus in the ordinary chernozem.

During 2024–2025 the ratio of humic acids to fulvic acids (HA/FA) exceeded 1.29 in almost all treatments, demonstrating the stability of the humus status of the studied soils. The only exception was the conventional tillage treatment in the first year of the experiment, where the HA/FA ratio was below 1.0, indicating a humate-fulvate type of humus with a relatively higher proportion of mobile humic compounds.

Table 7. Analysis of variance results

Parameter	p (Treatment)	p (Year)	p (Growth stage)	p (Tillage system	p (Fertilization)	p (Interaction)
Humus	<0.001	0.895	0.537	<0.001	<0.001	0.045
$N\text{-}NO_3$	0.781	0.003	<0.001	0.819	0.836	0.278
P_2O_5	0.004	0.054	0.001	0.038	0.001	0.247
K_2O	0.221	0.002	0.010	0.364	0.347	0.982
CO_2	0.700	0.679	<0.001	0.574	0.161	0.984
Total N	0.798	0.431	–	0.519	0.824	0.519

Continuation of Table 7

Organic carbon (SOC)	0.182	0.005	–	0.222	0.539	0.125
Labile carbon	0.116	0.001	–	0.585	0.146	0.353
Humic acids	0.723	0.304	–	0.634	0.600	0.939
Fulvic acids	0.894	0.110	–	0.513	0.745	0.638

Statistical analysis of the data was performed using analysis of variance (ANOVA) and Pearson correlation analysis (Table 7, 8). In the block model, the effects of the treatment, study year, and crop growth stage were evaluated. For the spring wheat treatments, a factorial ANOVA was additionally applied to assess the effects of tillage system, mineral fertilization and their interaction. Mean values were compared using the least significant difference test and differences were considered statistically significant at $p \leq 0,05$. Correlations among humus, $N\text{-}NO_3$, P_2O_5, K_2O and soil CO_2 emissions were evaluated using Pearson's correlation coefficient.

Table 8. Results of Pearson correlation analysis

Parameter	Humus	$N\text{-}NO_3$	P_2O_5	K_2O	CO_2
Humus	1.000	0.028	0.438*	0.143	0.113
$N\text{-}NO_3$	0.028	1.000	0.062	0.234	0.656*
P_2O_5	0.438*	0.062	1.000	0.492*	0.005
K_2O	0.143	0.234	0.492*	1.000	-0.117
CO_2	0.113	0.656*	0.005	-0.117	1.000

*Note: * - correlation is statistically significant at p≤0,05; n=30.*

Exploratory ANOVA showed that the experimental treatment had a statistically significant effect on humus content ($p < 0,001$) and plant-available phosphorus ($p = 0,004$). For humus, significant effects of the tillage system, mineral fertilization and their interaction were detected. The dynamics of $N\text{-}NO_3$ were primarily determined by study year and crop growth stage, whereas K_2O content was mainly influenced by year and sampling phase. Soil CO_2 emission was significantly affected by the seasonal growth stage ($p < 0,001$).

Pearson correlation analysis revealed a positive relationship between $N\text{-}NO_3$ and CO_2 emission ($r = 0,559$; $p = 0,001$). In contrast, the relationships between CO_2 emission and humus, P_2O_5 and K_2O were not statistically significant.

Discussion

The obtained results demonstrate that tillage system, mineral fertilization, and climatic conditions had a significant influence on the transformation of soil organic matter and the intensity of soil CO_2 emissions in the ordinary chernozems of Northern Kazakhstan. Year-to-year differences in climatic conditions were among the main factors regulating the soil carbon regime. The warmer and relatively drier conditions in 2025 promoted microbial activity and accelerated the mineralization of soil organic matter, resulting in lower contents of soil organic carbon and labile humus fractions, together with increased CO_2 emissions during the early stages of the growing season. Similar trends have been reported in previous studies, which showed that higher soil temperatures combined with limited soil moisture accelerate organic matter decomposition and increase carbon losses through CO_2 emissions [6, 15, 21].

The present findings confirm that the no-till system provides more favorable conditions for the preservation of soil organic matter than conventional tillage. Under no-till management, humus content remained relatively stable at 4.5–4.7%, whereas conventional tillage was associated with greater fluctuations and an overall declining trend. This can be attributed to reduced soil disturbance, the retention of crop residues on the soil surface and lower soil aeration, all of which limit the mineralization of organic matter. Similar findings were reported by *Reicosky* (2008) and *Cooper* et al. (2021), who demonstrated that reduced and no-till systems enhance soil organic carbon storage while mitigating greenhouse gas emissions [12, 20].

Higher levels of soil organic carbon and total nitrogen under the no-till system indicate a more stable functioning of the soil carbon-nitrogen cycle. The increased total nitrogen content observed in the no-till treatments suggests slower mineralization of organic compounds and more efficient preservation of nitrogen-containing organic matter. These findings are consistent with the concept of physically protected soil organic matter, whereby the maintenance of soil structure promotes carbon stabilization within microaggregates and organo-mineral complexes.

Changes in labile carbon content confirmed the high sensitivity of this fraction to both climatic and anthropogenic influences. The decline in labile carbon observed in 2025 reflects enhanced incorporation of organic matter into the biogeochemical cycle and increased microbial respiration. According to *Blair* et al. (2006), labile carbon is one of the most informative indicators of early changes in soil fertility and can be used to assess the resilience of agroecosystems to climate change [22].

The predominance of humic acids over fulvic acids (HA/FA > 1,29) indicates the development of a humate-type humus, which is characteristic of chernozem soils in the steppe zone. A high HA/FA ratio reflects the relatively stable nature of soil organic matter and slower dehumification processes. Nevertheless, the observed decline in labile carbon and soil organic carbon during the warmer year suggests a gradual intensification of organic matter mineralization under the influence of ongoing climate change.

The results obtained for soil CO_2 emissions confirm the important role of tillage practices in regulating soil respiration. The highest CO_2 emissions were recorded at the tillering stage, reaching 25.0 g CO_2 m^{-2} under conventional tillage with mineral fertilization. The increased emissions observed in the fertilized treatments can be explained by the priming effect, whereby mineral nitrogen application stimulates microbial activity and accelerates the decomposition of soil organic matter. Similar findings were reported by *Kuzyakov* et al. (2000), who demonstrated that the addition of readily available nitrogen enhances soil microbial respiration and increases carbon losses from the soil [23].

Despite the increase in CO_2 emissions during the early stages of crop development, the no-till system was characterized by a more stable soil carbon regime and lower seasonal variability in CO_2 emissions. These findings indicate more efficient carbon sequestration processes and reduced losses of soil organic matter under no-till management.

The dynamics of nitrate nitrogen and plant-available phosphorus further demonstrate the advantages of the no-till system. A more uniform distribution of these nutrients can be attributed to the retention of crop residues, reduced soil erosion, and a more stable soil moisture regime. Particularly noteworthy was the accumulation of plant-available phosphorus in the no-till + N30P20 treatment, where P_2O_5 concentrations reached 42.2–70.4 mg kg^{-1} after harvest. These findings indicate that conversation tillage practices are highly effective in maintaining a positive soil nutrient balance.

Overall, the findings demonstrate that, under the conditions of Northern Kazakhstan, the adoption of no-till management combined with moderate rates of mineral fertilization is an effective strategy for regulating the soil carbon balance, improving agroecosystem resilience, and maintaining the fertility of ordinary chernozem soils. In the context of projected increases in air temperature and growing climatic aridity, the implementation of no-till practices can be considered one of most promising approaches for adapting agricultural systems to climate change while enhancing the potential for soil carbon sequestration.

It should be noted that this study covers only a two-year observation period, whereas the transformation of soil organic matter and changes in soil carbon stocks are long-term processes. Therefore, a more comprehensive evaluation of the effectiveness of tillage systems requires long-term field experiments that account for interannual climatic variability, soil biological activity, and the overall greenhouse gas balance, including CO_2, N_2O, and CH_4. Such studies would provide a more robust assessment of the potential of conservation tillage practices to regulate the carbon cycle in the agricultural landscapes of Northern Kazakhstan.

Conclusion

The study demonstrated that:

Tillage systems, mineral fertilization and hydrothermal conditions significantly influenced soil CO_2 emissions, soil organic carbon content and the agrochemical properties of ordinary chernozem

in Northern Kazakhstan. In 2025, higher temperatures combined with a pronounced moisture deficit during June-August were accompanied by lower soil organic carbon and labile carbon contents compared with 2024, indicating more intensive transformation and mineralization of the readily decomposable fraction of soil organic matter and its greater involvement in the soil carbon cycle.

Soil CO_2 emissions exhibited pronounced seasonal dynamics. The highest CO_2 emission rates were recorded at the tillering stage of spring wheat under conventional tillage combined with mineral fertilization (N30P20). By the end of the growing season, CO_2 emissions declined due to reduced microbial activity and the depletion of readily available carbon substrates.

The no-till system promoted a more stable soil carbon cycle and enhanced the preservation of soil organic matter. Under no-till management, humus content remained relatively stable at 4.52–4.79%, whereas conventional tillage was associated with greater fluctuations and an overall decline in humus content.

Under the warmer conditions of 2025, soil organic carbon and labile carbon contents declined, indicating intensified mineralization of soil organic matter and greater incorporation of carbon into the biogeochemical cycle.

Higher total nitrogen and soil organic carbon contents were observed under the no-till system, particularly in the N30P20 fertilized treatment, indicating improved preservation of soil organic matter and more stable functioning of the soil carbon-nitrogen cycle.

The ordinary chernozem used in the study was characterized by moderate to high levels of plant-available phosphorus and a very high content of exchangeable potassium. The application of mineral fertilizers in combination with the no-till system promoted a more stable soil nutrient regime and enhanced the accumulation of plant-available phosphorus (P_2O_5) in the upper soil horizon.

The analysis of humus fractional composition revealed a consistent predominance of humic acids over fulvic acids (HA/FA >1,29), indicating the formation of a humate-type humus and the relatively high stability of soil organic matter in the ordinary chernozem.

Authors' Contributions

ZhA and AK: conceived the study and developed the research methodology. SK and GZ: performed the data analysis and prepared the main manuscript. GZ, DE, and GA: conducted the field experiments, processed the experimental data, and contributed to the interpretation of the results. All authors contributed to the discussion of the findings, critically revised the manuscript, and approved the final version for publication.

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Өңдеу жүйелерінің көмірқышқыл газының шығарылуына және қара топырақтың агрохимиялық күйіне әсері

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Түйін

Алғышарттар мен мақсат. Солтүстік Қазақстан жағдайында қара топырақтың (кәдімгі қара топырақ) агрохимиялық көрсеткіштері мен көмірқышқыл газының (CO_2) эмиссиясына топырақ өңдеу жүйелері мен минералдық қоректендірудің әсерін бағалау.

Материалдар мен әдістер. Далалық зерттеулер 2024–2025 жылдары Қарабалық ауыл шаруашылығы тәжірибе станциясында кәдімгі қара топырақта жүргізілді. Дәстүрлі және нөлдік топырақ өңдеу технологиялары, сондай-ақ, бақылау және минералдық тыңайтқыштар (N30P20) енгізілген жағдайдағы сүрі танап зерттелді. Топырақтан CO_2 эмиссиясының қарқындылығы жаздық бидайдың негізгі даму кезеңдерінде анықталды. Сонымен қатар, қарашірінді мөлшері, нитратты азот ($N\text{-}NO_3$), жылжымалы фосфор (P_2O_5) және алмаспалы калий (K_2O) мөлшері анықталды.

Нәтижелер. Зерттеу нәтижелері CO_2 эмиссиясының қарқындылығы топырақ өңдеу технологиясы мен минералдық қоректендіру деңгейіне тәуелді екенін көрсеттті. Көмірқышқыл газының ең жоғары бөлінуі түптену кезеңінде байқалып, минералды тыңайтқыш енгізілген дәстүрлі технология жағдайында 25,0 г $CO_2/м^2$ жетті. Вегетация кезеңінің соңында CO_2 эмиссиясы 2,1–4,1 $CO_2/м^2$ аралығына дейін төмендеді. 2025 жылғы ауа температурасының жоғары болуы органикалық заттардың минералдануын күшейтіп, көміртек айналымы үдерістерінің белсенділігін арттырды. Нөлдік технология дәстүрлі топырақ өңдеумен салыстырғанда қарашірінді мен минералдық қоректену элементтерінің анағұрлым тұрақты деңгейін қамтамасыз етті.

Қорытынды. Нөлдік топырақ өңдеу технологиясын минералдық қоректендірумен үйлестіріп қолдану топырақ құнарлылығын сақтауға және топырақтың көміртектік режимін тұрақтандыруға ықпал етеді, бұл Солтүстік Қазақстан жағдайында тұрақты егіншілік технологияларының тиімділігін арттырады.

Кілт сөздер: нөлдік технология; топырақ; минералды тыңайтқыштар; көмірқышқыл газының эмиссиясы; қарашірінді; топырақтың агрохимиялық көрсеткіштері.

Влияние систем обработки на эмиссию углекислого газа и агрохимическое состояние чернозёмов

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Аннотация

Предпосылки и цель. Оценить влияние систем обработки почвы и минерального питания на интенсивность эмиссию углекислого газа (CO_2) и агрохимические показатели чернозема обыкновенного в условиях Северного Казахстана.

Материалы и методы. Полевые исследования выполнены в 2024–2025 гг. на Карабалыкской сельскохозяйственной опытной станции на черноземе обыкновенном. Изучались традиционная и нулевая технологии обработки почвы, а также паровой участок на фоне контроля и внесения

минеральных удобрений (N30P20). Определяли интенсивность эмиссии CO_2 из почвы в основные фазы развития яровой пшеницы, содержание гумуса, нитратного азота ($N\text{-}NO_3$), подвижного фосфора (P_2O_5) и обменного калия (K_2O).

Результаты. Установлено, что интенсивность эмиссии CO_2 зависела от технологии обработки почвы, удобренности. Максимальные показатели выделения углекислого газа отмечались в фазу кущения и достигали 25,0 г $CO_2/м^2$ при традиционной технологии на удобренном фоне. К концу вегетации выделение эмиссии снижалась до 2,1–4,1 г $CO_2/м^2$. Более высокие температуры 2025 года способствовали усилению минерализации органического вещества и активизации углеродного обмена. Нулевая технология обеспечивала более стабильное содержание гумуса и элементов минерального питания по сравнению с традиционной обработкой.

Заключение. Нулевая технология обработки почвы в сочетании с минеральным питанием способствует сохранению плодородия почвы и стабилизации углеродного режима почвы, что повышает эффективность устойчивых технологий земледелия в условиях Северного Казахстана.

Ключевые слова: нулевая технология; почва; минеральные удобрения; эмиссия углекислого газа; гумус; агрохимические показатели почвы.