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Comparison of soil carbon dioxide emissions between conventional and conservation tillage systems in Križevci, Croatia

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Usporedba emisija ugljikovog dioksida iz tla između konvencionalne i konzervacijske obrade tla u Križevcima, Hrvatska

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ABSTRACT

This study evaluates the effects of different tillage systems on soil C-CO_2 emissions in winter wheat and maize cultivation in two consecutive years in a conventional and conservation agroecosystem. The influence of soil temperature, soil moisture and soil organic carbon (SOC) on soil C-CO_2 emissions should be investigated to gain insights into the relationships between environmental factors, soil properties and carbon fluxes during tillage. Soil C-CO_2 emissions were measured on Gleysol, in a temperate continental climate in northwestern Croatia in 2023 and 2024. Three different tillage systems were involved in the study: conventional tillage (CT), conservation tillage system deep (CTD) and conservation tillage system shallow (CTS). Fertilization was uniform across all treatments. Statistically significant differences between tillage systems were not observed in either year, indicating that tillage depth did not significantly affect annual soil C-CO_2 emissions under the studied conditions. However, significant differences were detected between the same treatments across different years. A weak relationship was observed between soil C-CO_2 emissions and both temperature and moisture across the two years. SOC levels did not differ significantly between treatments, although some visible variation was recorded. These findings underline the need for long-term monitoring of tillage practices for developing sustainable strategies to mitigate climate change and enhance soil carbon sequestration.

Keywords: soil respiration, cropland management, soil temperature, soil moisture, soil organic carbon, tillage system

SAŽETAK

Cilj istraživanja bio je procijeniti učinke različitih sustava obrade tla na emisije C-CO_2 iz tla u uzgoju ozime pšenice i kukuruza u dvije uzastopne godine u konvencionalnom i konzervacijskom agroekosustavu. Utjecaj temperature tla, vlažnosti tla te organskog ugljika (SOC) iz tla na emisije C-CO_2 ispitan je kako bi se dobio uvid u odnose između čimbenika okoliša, svojstava tla i tokova ugljika tijekom obrade. Emisije C-CO_2 iz tla mjerene su na Gleysolu, u umjereno kontinentalnoj klimi u sjeverozapadnoj Hrvatskoj 2023. i 2024. godine. U studiju su uključena tri tri različita sustava obrade tla: konvencionalna obrada (CT), konzervacijski sustav duboke obrade (CTD) i konzervacijski sustav plitke obrade (CTS). Gnojidba je bila ujednačena na svim tretmanima. Statistički značajne razlike između sustava obrade tla nisu utvrđene ni u jednoj godini, što ukazuje na to da dubina obrade nije imala značajan utjecaj na godišnje emisije C-CO_2 iz tla u istraživanim uvjetima. Međutim, statistički značajne razlike utvrđene su između istih tretmana u različitim godinama. Uočen je slaba pozitivna veza između emisija C-CO_2 iz tla te temperature i vlage tijekom dvije godine. Razine organskog ugljika nisu se značajno razlikovale između tretmana, iako su zabilježene vidljive varijacije. Rezultati istraživanja naglašavaju potrebu za dugoročnim praćenjem praksi obrade tla radi razvoja održivih strategija za ublažavanje klimatskih promjena i poboljšanje sekvestracije ugljika u tlu.

Ključne riječi: disanje tla, upravljanje obradivim zemljištem, temperatura tla, vlažnost tla, organski ugljik u tlu, sustav obrade tla

INTRODUCTION

Climate change is one of the greatest challenges of modern times, with effects observed at global, regional, and local levels (Rocha et al., 2022). Since the pre-industrial period, significant changes in the climate system have been driven by increased greenhouse gas emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which accumulate in the atmosphere and contribute to the warming of the planet (IPCC, 2022; Santos et al., 2022). These emissions are primarily caused by human activities in the energy, industry, transportation, and agriculture sectors. The burning of fossil fuels, deforestation, and intensive agricultural practices all contribute to rising concentrations of greenhouse gases in the atmosphere (West and Marland, 2002; Nunes, 2023). Agriculture alone emits significant amounts of CO_2 through land use change and soil disturbance, as well as CH_4 and N_2O from enteric fermentation, manure management, and fertilizer application. The changes in the climate system are already having visible consequences, including rising global temperatures, an increased frequency of extreme weather events such as heatwaves, droughts, floods, and hurricanes, as well as ocean acidification and biodiversity loss (Seneviratne et al., 2012; Clarke et al., 2022). Forecasts indicate that global temperatures will continue to rise and could exceed critical warming thresholds in the coming decades (IPCC, 2023). Such a scenario could lead to irreversible changes in ecosystems and social systems. With the continuous growth of the global population and shifts in consumption patterns, there is a growing need to maintain environmental quality to ensure the sustainability of agricultural production and other key sectors (Wang, 2022; Çakmakçı et al., 2023). As a contributor to climate change and at the same time an affected sector, agriculture plays a dual role: it generates emissions and at the same time offers mitigation potential through improved land management (Bilandžija et al., 2017; Lynch et al., 2021; Lal et al., 2021; Rodrigues et al., 2023; Galić, 2024). It is estimated that the first meter of soil can store about 1500 Pg (petagrams) of organic carbon, a significant portion of which is concentrated in the upper layers, where microbial activity and decomposition of organic matter are most intense (Li et a., 2021; Stockmann et al., 2013; Tanveer et al., 2020). Appropriate agricultural practises therefore help to maintain and increase the carbon stocks in the soil as well as the carbon stored in the plant biomass (Bilandžija et al., 2016). Numerous studies have shown that SOC are strongly influenced by different management strategies such as tillage, fertilization, and irrigation, all of which contribute to CO_2 sequestration (Lal, 2004; Galić et al., 2023; Yao et al., 2024; Šimon et al., 2024). Thus, considering its central role in carbon storage, SOC is one of the most critical indicators of soil health and a key factor in climate change mitigation. In addition, soil-related environmental variables, including moisture and temperature, as well as management and vegetation factors such as cover crops, have a significant impact on key mechanisms of the carbon cycle (Bilandžija et al., 2021a; Ozlu et al., 2022; Bilandžija et al., 2023; Chataut et al., 2023). Among these management practices, tillage plays a particularly important role in soil CO_2 emissions, as it disrupts soil structure, increases aeration, and accelerates organic matter decomposition, leading to higher carbon release into the atmosphere (Kristof et al., 2014; Singh et al., 2024). Given the strong role of soil moisture in regulating these processes, soil type represents an important framework for evaluating management effects on carbon fluxes (Jones and Naiman, 2006; Yang et al., 2018). Gleysols, widespread in continental Croatia and characterized by periodic water saturation, were therefore selected due to their sensitivity to soil disturbance and moisture variability (Jug et al., 2024). Therefore, understanding soil carbon dynamics is crucial to advancing sustainable management strategies and minimize greenhouse gas emissions. Due to the lack of national measurements, the Croatian greenhouse gas inventories were mainly based on standard IPCC emission factors derived from data from other countries. One of the IPCC's key recommendations for improving the accuracy of greenhouse gas reporting is the development of country-specific emission factors. This study, therefore, makes an important contribution to closing this national data gap.

This study investigates the effects of different tillage systems on soil C-CO_2 emissions in winter wheat and maize cultivation in two consecutive years, taking into account the effects of fertilization and environmental factors. The specific objectives of this study are: (1) to compare and evaluate the effects of different tillage systems (conventional and conservation tillage) on CO_2 emissions, (2) to evaluate the influence of soil temperature, soil moisture, and SOC on soil C-CO_2 emissions in winter wheat and maize fields under different tillage systems.

MATERIALS AND METHODS

Study site

The trial was conducted in 2023 and 2024 in northwestern Croatia (location Križevci - 16°33′32″ E; 46°01′38″ N) at an altitude of 141 m above sea level. The soil type is classified as Gleysol (WRB, 2006), a hydromorphic soil type characterized by periodic excess moisture throughout the year. The basic description of the soil texture, physical, and chemical properties is shown in Table 1 to characterize the experimental site (Jug et al., 2024).

Figure 1. Study site location and view of the experimental plots in Križevci, Croatia (Source: Google Earth, 2024; Mikec, 2023)

Table 1. Mechanical, physical, and chemical soil properties

Gleysol	0–36 cm	36–97 cm	97–175 cm	Method
Soil texture				
Silt (%)	82.95	80.41	78.96	
Clay (%)	9.61	14.08	14.90	HRN ISO 11277:2004
Sand (%)	7.44	5.52	6.15	
Physical properties				
Field capacity (vol.%)	42.44	37.69	36.31	Gračanin, JDPZ, 1971
Particle density (g/cm^3)	2.69	2.73	2.78	HRN ISO 11508:2004
Bulk density (g/cm^3)	1.51	1.73	1.79	HRN ISO 11271:2004
Total porosity (%)	47.21	41.39	39.91	HRN ISO 11508:2004
Chemical properties				
pH (KCl, 1:5)	5.22	5.73	5.68	HRN ISO 10390:2004
P_2O_5 (AL), mg/kg soil	154	26	32	AL method, Egner et al., 1960.
K_2O (AL), mg/kg soil	75	52	48	AL method, Egner et al., 1960.
Soil Organic Matter - (%)	1.64	0.52	0.41	Modified HRN ISO 14235:1998

The mean annual temperature and total precipitation for the investigated years (2023–2024) and the reference period (1991–2020) are shown in Figure 2. According to Köppen's climate classification, the climate is "Cfb" – temperate with mild winters and moderately warm summers, with an even distribution of precipitation throughout the year (Kottek et al., 2006). In 2023, total precipitation was 1088.2 mm, with the highest value recorded in January (148.1 mm) and the lowest in September (34.0 mm). The average annual temperature was 12.6 °C, with February being the coldest month (3.5 °C) and July the warmest (22.7 °C). In 2024, total precipitation fell to 839 mm, with a maximum in September (140.4 mm) and a minimum in August (27.5 mm). The average annual temperature was 13.2 °C, with January being the coldest month (1.2 °C) and July and August the warmest months (24.2 °C). Compared to the reference period (1991–2020), in which the average annual temperature was 11.1 °C and the annual precipitation was 807.3 mm, both study years were warmer, with 2024 showing the greatest deviation (+2.1 °C). Precipitation in 2023 was well above the reference average (+35%), while in 2024 it was closer to the long-term average (+4%).

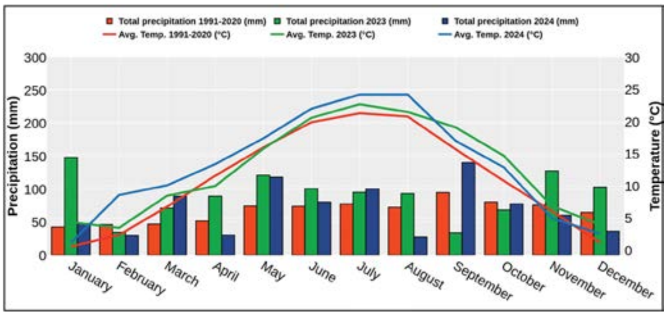


Figure 2. Monthly precipitation amount (mm) and mean temperature (°C) in the reference period 1991-2020 and the periods investigated 2023 and 2024

Experimental design

The trial was designed as a completely randomized block trial with three different tillage systems and conducted on a total area of 15 000 m^2. (Figure 1). The basic plot size was 160 m^2. The distance between the different tillage treatments was 2 m on each side and 1 m between replicates. The tillage systems were: CT-conventional tillage (based on plowing up to 30 cm); CTD-conservation tillage system deep (soil loosening up to 30 cm with a minimum crop residue cover of 30% on the soil surface) and CTS-conservation tillage system shallow (soil loosening up to 10 cm depth with a minimum crop residue cover of 50% on the soil surface). Fertilization was uniform across all treatments and followed the recommendation of fertilizers using mineral fertilizers. The applied fertilizers included NPK (0–20–30, containing P_2O_5 and K_2O), KAN (calcium ammonium nitrate, 27% total nitrogen), and UREA (46% nitrogen) (Table 2). The NPK was calculated as described in Jug et al. (2024) and applied evenly across all tillage treatments according to the same distribution pattern. In the first year of the study, all primary tillage operations (CT, CTD, and CTS) and fertilization were carried out on 20 October 2022. In the second year, all primary tillage operations and fertilization were carried out on 14 November 2023, while KAN fertilization was applied on 11 April 2024.

During the study period, winter wheat (*Triticum aestivum* L. – variety Indira, 250 kg/ha) was grown on the experimental field in 2023, followed by maize (*Zea mays* L. – hybrid Gloriett, FAO 300, 75 000 grains/ha) in 2024. Table 2 contains information on the seeding and harvest dates, as well as the fertilization and plant protection practices applied during the study. Other relevant information about the experimental site was previously reported by the authors Jug et al. (2024).

Measurement of soil CO_2 concentration and agroecological factors

The CO_2 concentration in the soil was measured nine times in 2023 and seven times in 2024. The measurements took place in the following months: March, April, May, June, July, August, September, October, and November in 2023, and in April, May, June, July, August, September, and November in 2024. Each treatment included three replicates of the measurements. The methodology followed the approach described in Galić et al. (2023). For the measurements of CO_2 concentration in soil, the in situ closed static chamber method was used.

Table 2. Seeding time, harvest time, fertilization and plant protection during the vegetation years

Vegetation Year	Seeding date	Harvest Date	Fertilization	Crop protection
2023	21 October 2022	12 July 2023	NPK 615 kg/ha (0:20:30), KAN 388 kg/ha, UREA 0 kg/ha	- Qulex 50g/ha, axial 0.5 l/ha, Elatus era 1l/ha, Cythrin max 50ml/ha - Prosaro 1l/ha, Karate Zeon 0.15l/ha
2024	2 May 2024	25 September 2024	NPK 750 kg/ha (0:20:30), KAN 444 kg/ha, UREA 98 kg/ha	- Adengo 2.5l/ha + Elumis Peak 4.5l+60g – 1.5 l/ha - 20 kg/ha Force 1.5G (Syngenta)

The chambers are custom-made, constructed of light-proof metal material, and consist of circular frames and caps equipped with a gas sampling port. The frames were inserted 10 cm into the soil at the beginning of the measurements. Before closing the chamber, the initial CO_2 concentration was measured. After closing the chamber on the soil surface, CO_2 accumulation was allowed during a 30-minute incubation period. After the incubation period, the portable IR detector (GasAlertMicro5 IR, 2011) was directly connected to the chamber via the gas sampling port, and CO_2 concentration (ppm) was measured, and soil CO_2 flux was calculated from the increase in CO_2 concentration over time:

$FCO_2 = [M \times p \times V \times (c_2 - c_1)]/[R \times T \times A \times (t_2 - t_1)]$ (Table 3).

Air temperature, relative humidity and air pressure were recorded during each CO_2 measurement with Testo 511 and Testo 610 (2011) at a height of ~0.5 m above the soil surface. Soil temperature, moisture and electrical conductivity were measured with an IMKO HD2 and Trime Pico64 probe (2011). Two probes were inserted 10 cm deep into the soil near each chamber.

Data analysis

The statistical analysis was performed using SAS software, version 9.1 (SAS Institute Inc., 2002–2004, Cary, NC, USA). Variations from year to year and differences between treatments within the same year and across different months were assessed using analysis

Table 3. Parameters and units for soil CO_2 flux calculation

Symbol	Description	Unit
FCO_2	soil CO_2 efflux	kg/ha per day
M	molar mass of the CO_2	kg/mol
P	air pressure	Pa
V	chamber volume	m^3
c_1	CO_2 concentration at the beginning of the measurement	µmol/mol
c_2	CO_2 concentration at the end of the measurement	µmol/mol
R	the gas constant	J/mol/K
T	air temperature	K
A	chamber surface	m^2
t_2-t_1	incubation period	day

of variance (ANOVA), followed by a Fisher's post hoc t-test. All statistical tests were based on a significance level of 5%. Regression analysis was conducted to assess the relationships between soil C–CO_2 emissions and soil temperature and soil moisture measured at 10 cm depth. The relationships between soil C–CO_2 emissions and soil organic carbon (SOC) content were analyzed using Pearson correlation analysis. All analyses were performed independently for each year. The strength of the correlation between soil carbon dioxide emissions and agro-ecological factors was interpreted using the Roemer-Orphal scale (Vasilj, 2000).

RESULTS

Soil C-CO_2 emissions during the investigated years

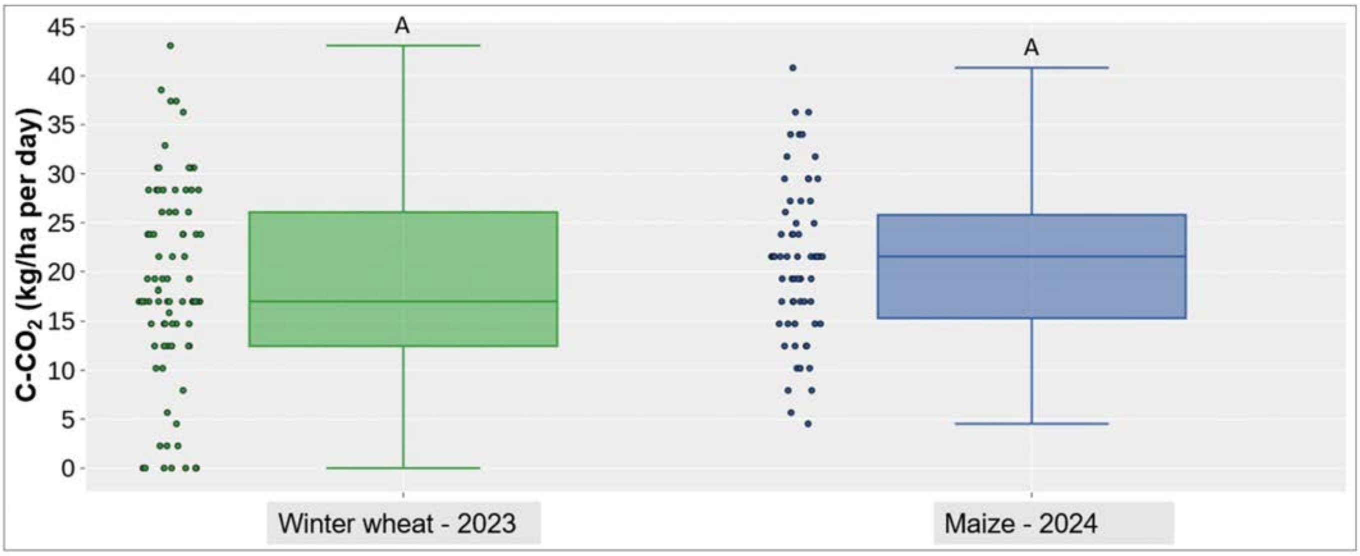
Figure 3 shows the average annual soil C-CO_2 emissions for the years studied and the corresponding crops. The recorded emissions were 18.74 kg/ha per day in 2023 and 21.07 kg/ha per day in 2024, without a statistically significant difference between the two years.

The soil C-CO_2 emissions for three different treatments (CT, CTD and CTS) in two growing seasons are presented in Figure 4. In 2023, emissions were highest for CT treatment (20.53 kg/ha per day), followed by CTD (18.56 kg/ha per day) and CTS (17.47 kg/ha per day). In 2024, emissions under CTS (22.67 kg/ha per day) and CTD (22.24 kg/ha per day) were slightly higher than under CT (18.30 kg/ha per day). In both years, no statistically significant difference was found between the three treatments studied. When comparing the same treatments in the two years, statistically significant differences were found in all treatments (Figure 5).

Figure 6 presents the average daily C-CO_2 fluxes for three tillage treatments in 2023 and 2024. In 2023, emissions ranged from 0.01 kg/ha per day in November to a peak of 37.03 kg/ha per day in May. In 2024, the values ranged from 8.69 kg/ha per day in April to a maximum of 31.37 kg/ha per day in July. Although no statistically significant differences were found in 2023, variations in C-CO_2 emissions depending on the treatment are observed. In 2024, statistically significant differences were found between treatments in May and September.

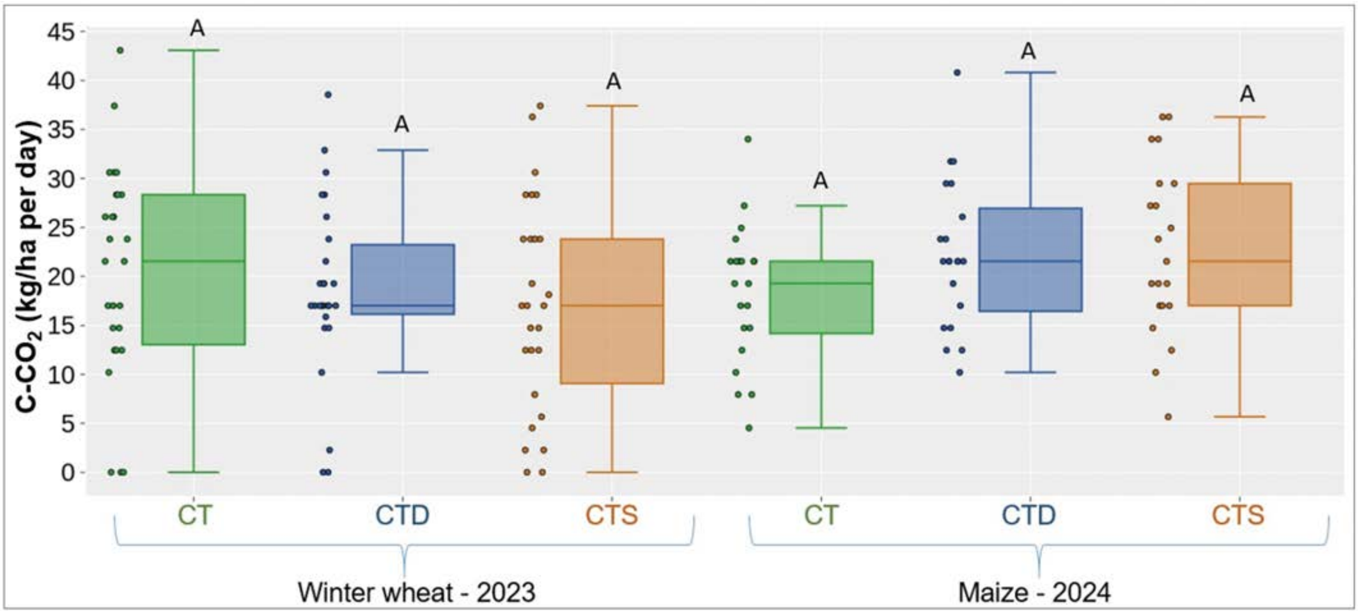
Correlation between C-CO_2 emissions and SOC

The correlation between soil C-CO_2 emissions and soil organic carbon (SOC) content at 0–15 cm and 15–30 cm depth was analysed using Pearson correlation analysis.



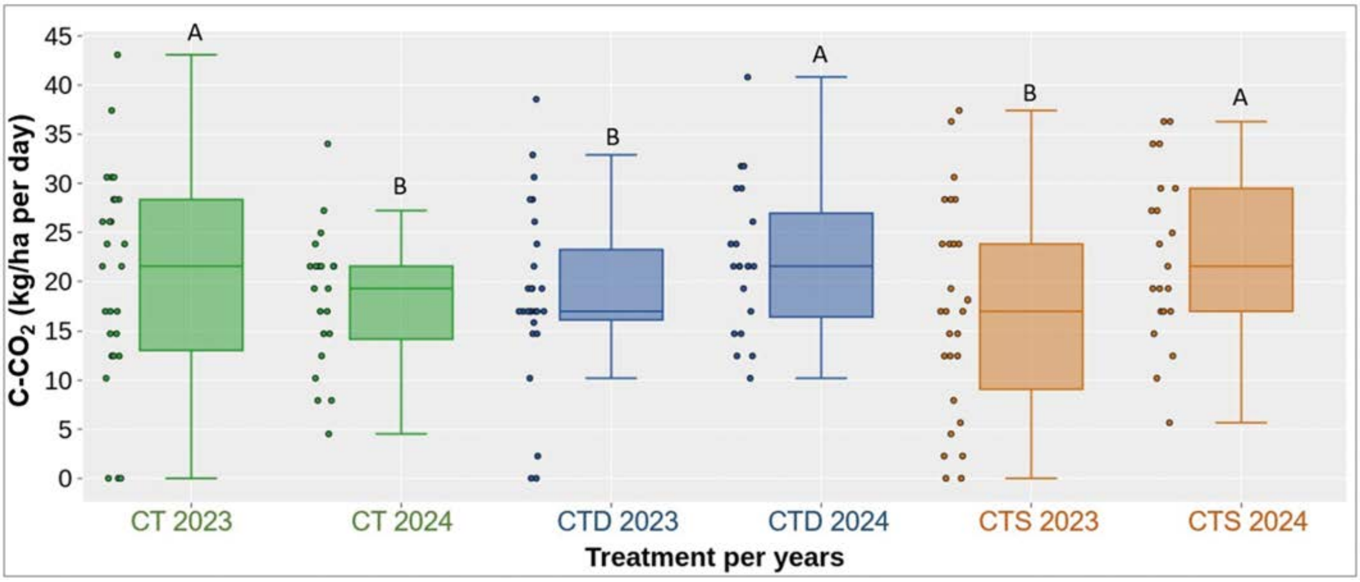
The box plot shows the maximum (upper hanging bar), the minimum (lower hanging bar), the third quartile (upper box line), the median (line) and the first quartile (lower box line). Statistically significant differences between the two years (crops) are indicated by different letters (A, B) (*P* < 0.05)

Figure 3. The average annual soil C-CO_2 emission values for 2023 (n = 81) and 2024 (n = 63)



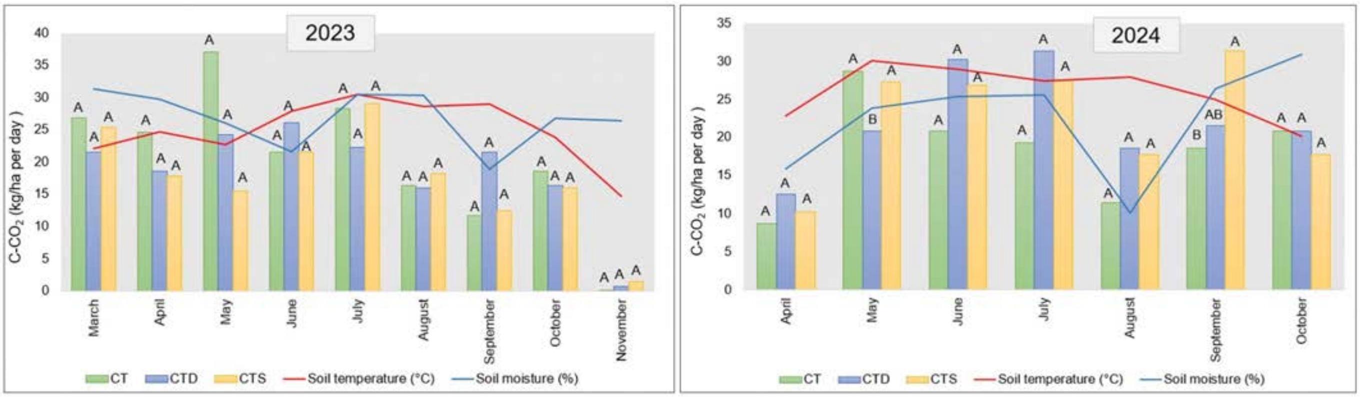
The box plot shows the maximum (upper hanging bar), the minimum (lower hanging bar), the third quartile (upper box line), the median (line) and the first quartile (lower box line). Statistically significant differences between three treatments in two years are indicated by different letters (A, B) ($P < 0.05$).

Figure 4. Average annual values of soil C-CO$_2$ emissions by treatments in winter wheat and maize vegetation



The box plot shows the maximum (upper hanging bar), the minimum (lower hanging bar), the third quartile (upper box line), the median (line) and the first quartile (lower box line). Statistically significant differences between the same treatments in two years are indicated by different letters (A, B) ($P < 0.05$).

Figure 5. Comparison of soil C-CO$_2$ emissions for the same treatments in 2023 and 2024



Statistically significant differences between three treatments are indicated by different letters (A, B) ($P < 0.05$).

Figure 6. Average daily soil C-CO_2 emissions (kg/ha per day) in relation to soil temperature (°C) and soil moisture (%) at 10 cm depth during the investigated period

Table 4 shows that the correlation coefficients (r) remained low in both years, indicating none to very weak linear relationships between C-CO_2 emissions and SOC content in the soil layers and tillage treatments. The correlation between C-CO_2 emissions and SOC content at 0–15 cm ranged from r = 0.1523 in 2023 (CTD) to r = 0.2217 in 2024 (CTS). At the 15–30 cm depth, the correlation ranged from r = –0.1253 in 2023 (CTD) to r = 0.1393 in 2024 (CTD). Although none of the relationships reached statistical significance (*P*>0.05), some variation was observed between treatments.

Table 4. Correlation between soil C-CO_2 emissions and soil organic carbon (SOC) content at two soil depths for 2023 and 2024

		P-value	Coefficient of correlation (r)	Strength of correlation
		2023		
CT	0-15 cm	0.628 ns	0.0977	None
	15-30 cm	0.640 ns	-0.0943	None
CTD	0-15 cm	0.448 ns	0.1523	Very weak
	15-30 cm	0.533 ns	-0.1253	Very weak
CTS	0-15 cm	0.577 ns	0.1116	Very weak
	15-30 cm	0.779 ns	-0.0566	None
		2024		
CT	0-15 cm	0.934 ns	-0.0194	None
	15-30 cm	0.887 ns	0.0331	None
CTD	0-15 cm	0.577 ns	-0.1292	Very weak
	15-30 cm	0.547 ns	0.1393	Very weak
CTS	0-15 cm	0.334 ns	0.2217	Very weak
	15-30 cm	0.605 ns	0.1197	Very weak

Level of statistical significance: *-$P \le 0.05$; **-$P \le 0.01$; ***-$P < 0.001$; ns-not significant.
CT - conventional tillage; CTD - conservation tillage system deep; CTS - conservation tillage system shallow

Correlation between C-CO_2 emissions and soil properties

The relationship between soil C-CO_2 emissions and soil temperature at a depth of 10 cm was analysed using a regression analysis for the years studied. As Figure 7 shows, the correlation coefficients (r) were low in both years, indicating a weak dependence between soil C-CO_2 emissions and soil temperature in 2023 (r = 0.37) and 2024 (r = 0.36). The coefficient of determination (R^2) values further confirmed this weak relationship, showing that soil temperature accounted for only 14.2% of C-CO_2 emissions in 2023 and 13.4% in 2024. Overall, the results indicate that although soil temperature contributed to an increase in C-CO_2 emissions, its influence remained relatively weak throughout the observation period. In addition, the relationship between C-CO_2 emissions and soil moisture was analysed by regression analysis. As shown in Figure 8, the correlation in 2023 was minimal (r = 0.06), while a much stronger correlation was found in 2024 (r = 0.52). In 2023, the R^2 value of 0.0039 indicated that only 0.4% of C-CO_2 emissions were influenced by soil moisture. In 2024, however, the R^2 value of 0.2764 indicated that soil moisture was responsible for 27.6% of the variation in C-CO_2 emissions. These results show that soil moisture had little influence in 2023, while it played a greater role in regulating soil C-CO_2 emissions in 2024.

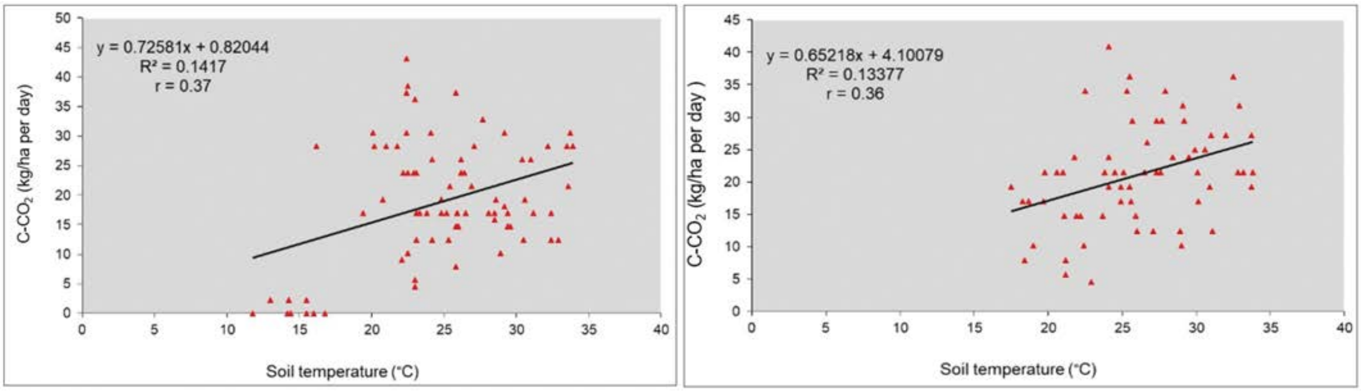


Figure 7. Correlation between soil C-CO_2 emissions and soil temperature (°C) at 10 cm depth for 2023 (left) and 2024 (right)

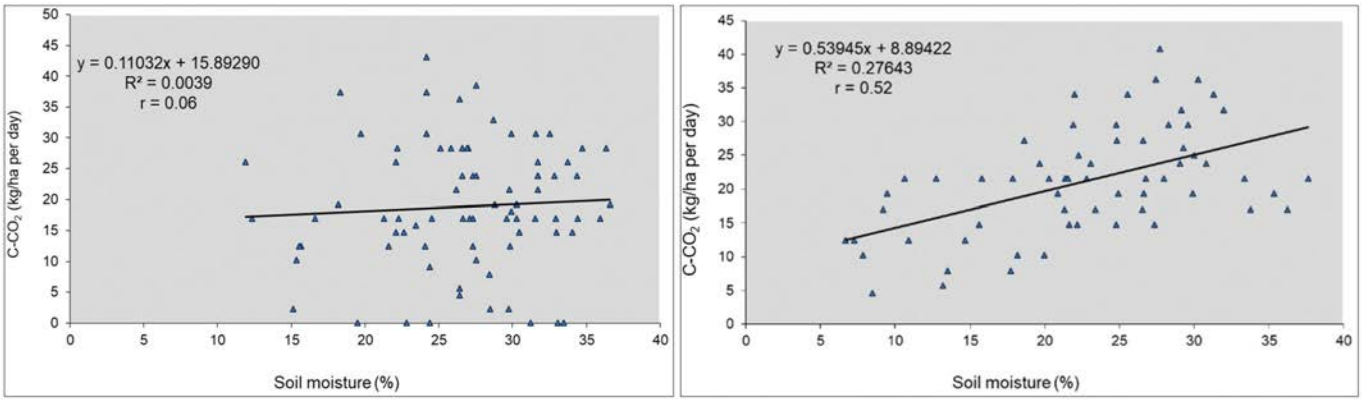


Figure 8. Correlation between soil C-CO_2 emissions and soil moisture (%) at 10 cm depth for 2023 (left) and 2024 (right)

DISCUSSION

The amount of greenhouse gases emitted from agricultural land is not uniform, but depends on interacting factors including crop type, management practices and environmental conditions. In this study, the annual C-CO_2 emissions from soil during the winter wheat cultivation were 11.06% lower than during maize, although the difference was not statistically significant (Figure 3). One of the reasons for the lower C-CO_2 emissions during the vegetation of winter wheat could be the higher soil cover, which reduces water evaporation and stabilises the microclimatic conditions in the soil (Kanzler et al., 2019; Mubvumba et al., 2021). This is supported by the 18.58% higher average soil moisture recorded during winter wheat vegetation compared to maize. Although increased soil moisture is generally associated with enhanced microbial activity, its effect on soil respiration is not linear and depends on accompanying environmental conditions. Lower temperatures during winter wheat cultivation may have reduced microbial activity and slowed the decomposition of organic matter, whereas higher soil temperatures during maize vegetation may have stimulated microbial processes, contributing to increased C-CO_2 emissions (Moinet et al., 2018; Tolunay et al., 2024; Chen et al., 2019; Wu et al., 2020; Huang et al., 2025). Additionally, the differences in crop phenology, root biomass and residue inputs between winter wheat and maize may have further influenced carbon turnover. Similar patterns have been reported in winter wheat–maize rotation systems under temperate conditions, where soil respiration was higher during maize cultivation than during winter wheat. These differences were explained by higher soil temperatures, greater biomass production and increased root-derived carbon inputs during the maize growing season, which enhanced microbial activity and CO_2 efflux (Huang et al., 2016). However, in contrast to these results, some previous studies have observed higher CO_2 emissions from winter wheat than from maize or other crops, which were attributed to differences in fertilization intensity, soil moisture availability and crop growth duration that enhanced carbon mineralization (Cheng et al., 2015; Zhang et al., 2018).

The effects of tillage on soil CO_2 emissions are well-documented due to their influence on soil aeration and organic matter mineralization (Bilen et al., 2010; Maharjan et al., 2018). In this study, differences in C-CO_2 emissions between 2023 and 2024 varied between treatments, suggesting that both soil management practices and crop type influenced carbon fluxes (Figures 4 and 5). In the CT treatment, C-CO_2 emissions decreased in 2024 compared to 2023, reflecting interactions between crop type and environmental conditions (Figure 4). The observed increase in emissions in CTD and CTS treatments in 2024 (Figure 4) suggests that tillage intensity and soil disturbance can significantly affect microbial activity and carbon mineralization. Previous studies have shown that greater soil disturbance enhances microbial activity and accelerates organic matter decomposition, potentially leading to higher CO_2 emissions (Lal,2004; Bilen et al.,2010; Buivydienė et al., 2024. However, the effectiveness of conservation tillage in reducing emissions remains variable and is influenced by climatic conditions, soil properties and the degree of disturbance (Bilandžija, 2015; Jug et al., 2017; Meng et al., 2024) In this study, the difference between CTS and CTD treatments was 1.09 kg/ha per day in 2023 and 0.43 kg/ha per day in 2024 (Figure 4), confirming that reduced tillage depth alone had a limited effect on annual C-CO_2 emissions under the prevailing conditions. This pattern is consistent with regression analysis in this research, which showed weak relationships between emissions and soil temperature, whereas soil moisture exhibited a stronger association with C-CO_2 dynamics during the study period (Figures 7 and 8). Some studies have reported a decrease in soil CO_2 emissions (Abdalla et al., 2019; Ma et al., 2019), while others have observed an increase (Fan et al., 2018; Locker et al., 2019), or no significant change at all (Dendooven et al., 2012), depending on the different conservation practices.

It is important to note that while tillage systems varied, fertilization was consistent across treatments in both years (Table 2). However, the increased application of NPK, KAN, and UREA in 2024 compared to 2023 may have contributed to seasonal differences in C-CO_2 emissions. Fertilizer inputs, particularly nitrogen, can stimulate microbial activity and organic matter decomposition, potentially enhancing CO_2 emissions under favourable temperature conditions (Choi et al., 2011; Khan et al., 2023; Wang et al., 2024). In the cooler months, from November to March, when microbial activity is typically lower due to lower temperatures and lower microbial diversity in the soil, the impact of fertilization on emissions may have been minimal (Maron et al., 2018).

Short-term fluctuations in soil respiration observed during this study period likely reflect the combined influence of management and environmental conditions. Soil respiration is ultimately linked to the size and turnover of SOC pools, which represent the primary substrate for microbial decomposition (Thotakuri et al., 2024). In contrast to short-term flux dynamics, SOC changes more slowly and plays a central role in long-term CO_2 emissions, soil health and function (Mason et al., 2023). The weak correlations observed between SOC and C-CO_2 emissions (Table 4) may reflect the relatively limited variation in SOC values during the three-year period. SOC at 0–15 cm ranged from 0.86% to 1.72% in 2023 and from 1.12% to 1.26% in 2024 across treatments, while at 15–30 cm it ranged from 1.14% to 1.79% in 2023 and from 1.00% to 1.16% in 2024. Such relatively narrow ranges are expected over short experimental periods, as measurable changes in SOC often require long-term management. This results are supported by long-term field studies, according to which even a decade of continuous cultivation, especially with conservation tillage, is often not sufficient to cause a measurable increase in SOC stocks (Roth et al., 2023; Ibrahim et al., 2024), and changes in soil CO_2 efflux. Overall, results suggest that although short-term changes in SOC are limited, early trends may represent the beginning of longer-term shifts in carbon dynamics with continued management.

Furthermore, soil CO_2 emissions exhibited seasonal dynamics associated with changes in soil temperature and moisture (Galić et al., 2020; Bezyk et al., 2023). Emissions were generally higher in spring and summer months, and lower in autumn and winter, consistent with more favourable conditions for microbial activity during the warmer periods (Bilandžija et al., 2014; Galić et al., 2022; Luo and Zhou, 2006). A similar seasonal pattern was observed in both 2023 and 2024 (Figure 5). However, despite the general trend of emissions increasing with increasing temperatures, the regression analysis shows that soil temperature alone was not a strong predictor of C-CO_2 emissions during the study period (Figure 6). This suggests that emission dynamics during the study period were influenced by interacting effects of soil moisture, crop-specific characteristics and temperature. The decline in emissions during July and August, despite high soil temperatures, highlights the limiting role of low soil moisture during dry summer periods (Darenova et al., 2023; Lemoine et al., 2023). In addition, the analysis shows that the influence of soil moisture on C-CO_2 emissions was stronger in 2024 than in 2023 (Figure 7). The observed fluctuations may be due to variations in soil moisture during the growing season, which emphasises that C-CO_2 emissions respond to moisture dynamics. These results are in good agreement with observations from previous studies, which emphasized that the availability of soil moisture during dry periods can become a limiting factor for microbial activity despite favorable temperature conditions (Davidson and Janssens et al., 2006). In 2024, statistically significant differences between treatments indicate that different tillage practices can influence emissions through changes in soil structure, aeration and moisture availability (Figure 5) (Mühlbachová et al., 2023), supporting earlier findings that different tillage practices can alter microclimatic conditions and thus influence soil respiration rates (Alhassan et al., 2021; Mühlbachová et al., 2023).

In the study by Zhang et al. (2018), soil temperature and soil moisture explained up to 70% of soil CO_2 emissions with and up to 78% without root influence. However, in agroecosystems, seasonal CO_2 dynamics are not controlled by environmental factors alone, but also by crop-specific characteristics and vegetation cover. In this study, winter wheat (2023) and maize (2024) were included as part of the planned crop rotation system, representing typical regional management practices. Differences in canopy structure, root biomass, phenology and residue input between these crops likely contributed to the observed seasonal and interannual variability in C-CO_2 emissions. Vegetation influences carbon dioxide emissions through photosynthesis, root respiration and decomposition of plant material (Shi et al., 2020; IPCC, 2021; Rodrigues et al., 2023). Higher emissions recorded in spring and summer in both years coincide with periods of active crop growth, when root respiration and microbial degradation of fresh organic inputs are intensified. Conversely, lower emissions during autumn and winter correspond to reduced plant activity and lower biological inputs to the soil. These findings indicate that seasonal emission patterns reflect the combined influence of climatic conditions and crop-specific biological processes rather than a single dominant driver. Similar observations have been reported by several authors (Kato et al., 2012; Neira et al., 2015; Galić et al., 2020; Bilandžija et al., 2021).

CONCLUSION

This study has shown that different tillage systems significantly influence C-CO_2 emissions in agricultural agroecosystems. The average annual soil C-CO_2 emissions were lower under winter wheat than maize, due to the higher soil cover, greater moisture content, and lower temperatures. In contrast, the higher temperatures during maize vegetation stimulated microbial activity and organic matter decomposition, resulting in higher C-CO_2 emissions. The differences in C-CO_2 emissions between 2023 and 2024 varied between tillage treatments, suggesting that both management practices and crop type play a crucial role in regulating carbon fluxes. Seasonal dynamics were evident, with emissions generally lower in the colder months and more pronounced differences between treatments in warmer months. While higher soil temperatures can promote microbial activity, summer droughts can limit emissions due to reduced water availability. Although fertilization was consistent across treatments, it may also have influenced microbial activity and soil health, possibly contributing to the observed seasonal variation in C-CO_2 emissions. The influence of agro-ecological factors, i.e. soil temperature, on CO_2 emissions was weak in both years, while the influence of soil moisture ranged from very weak to strong. Although no significant changes in SOC were observed over the two-year period, the trends suggest that longer monitoring is needed to assess the potential for carbon accumulation under management practices. The results obtained highlight the importance of tailoring soil and fertilizer management practices that take specific agro-ecological factors into account. Applying conservation tillage practices, optimizing fertilization, and increasing soil carbon storage can help reduce greenhouse gas emissions and improve the sustainability of agricultural systems. Future studies should focus on long-term analyses of the interactions between climate factors, SOC, tillage, and fertilization in order to develop effective strategies to reduce the negative impacts of agriculture on climate change.

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