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Long-Term Effects of Different Tillage Systems and Their Impact on Soil Properties and Crop Yields

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Abstract: The scientific aim of this article is to elucidate the effects of various tillage practices on soil properties and crop yields; additionally, it seeks to highlight the significant potential of specific farming systems in enhancing soil organic carbon, thereby positively influencing CO_2 emissions from soil. In the experimental station of Vytautas Magnus University, Kaunas District, Lithuania (54°52′50′′ N and 23°49′41′′ E), a long-term field experiment has been established since 1999, and studies have been conducted since 2003. The soil of the experimental site is classified as Epieutric Endocalcaric Planosol (Endoclayic, Episiltic, Aric, Drainic, Endoraptic, Uterquic), according to the World Reference Base (WRB, 2022). Two primary factors were assessed. Factor A incorporated practices of straw removal versus straw chopping and spreading, while Factor B evaluated a spectrum of tillage techniques: conventional deep plowing and two no-tillage practices, one of which involved cover crops. The findings from this long-term study highlight a significant increase in SOC stocks across all treatments over the 20-year period. Notably, the no-tillage practices, coupled with the spreading of chopped straw, demonstrated the most substantial growth in SOC levels, particularly in the top 0–10 cm soil layer. This trend underscores the effectiveness of minimizing soil disturbance and incorporating organic matter in boosting SOC stocks. The different tillage systems influence CO_2 emissions from soil. Initially, direct sowing into uncultivated land, both with and without cover crops, led to a notable reduction in CO_2 emissions compared to conventional plowing. However, this effect was found to vary over the growth cycle of the plant, highlighting the dynamic interaction between tillage practices, soil properties, and environmental conditions. Collaborative research efforts that involve farmers, scientists, policymakers, and other stakeholders are crucial for the development of holistic, practical, scalable solutions that enhance the sustainability and productivity of agricultural systems. This study contributes to the growing body of knowledge on sustainable agriculture, providing insights for farmers, agronomists, and policymakers in their quest to promote environmentally sound and productive agricultural systems.

Keywords: soil organic carbon; CO_2 emissions; soil resilience; crop yield; sustainable agriculture

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1. Introduction

Agriculture, an ancient practice shaping landscapes and livelihoods, has evolved considerably, particularly in its interaction with soil ecosystems [1]. Soil, a critical component of the terrestrial ecosystem, is the foundation for plant growth and agricultural productivity [2]. However, traditional agricultural practices, particularly various tillage systems, have profound and diverse impacts on soil properties and crop yields [3–5]. The advent of sustainable agriculture necessitates a comprehensive understanding of these effects to inform practices that harmonize crop productivity with environmental stewardship [6].

The long-term effects of different tillage systems were investigated in this study, focusing on conventional deep plowing, shallow plowing, plowless tillage, single seedbed discing, and two distinct no-tillage practices, one of which incorporates cover crops [7]. These systems represent a spectrum of soil disturbance intensities, each with unique implications for soil structure, moisture, nutrient dynamics, and microbiological activity. This study is primarily centered on how soil tillage system practices influence soil organic carbon (SOC) levels and subsequent carbon dioxide (CO_2) emissions, which are pivotal factors in both soil health and global carbon cycling [8–11].

Soil organic carbon is a key indicator of soil quality, influencing soil structure, nutrient availability, and water retention [12]. Enhanced SOC levels are generally associated with improved soil resilience, a crucial characteristic in the face of climate change and increasing environmental stressors. Moreover, soil acts as a significant carbon sink, and its management is integral in the discourse on greenhouse gas emissions and climate change mitigation. In this context, it is vital to understand the dynamics of SOC under different tillage regimes [13,14]. The critical role of agriculture in both contributing to and mitigating climate change is becoming increasingly evident. Central to this discussion is the understanding of how different farming systems impact soil characteristics, including the release of CO_2 emissions, soil resilience, and ultimately plant productivity. Recent long-term studies have brought to light the significant potential of certain agricultural practices in enhancing soil health and function, with notable implications for carbon cycling and ecosystem sustainability [15–18].

Soil serves not only as a foundation for plant growth but also as a significant carbon reservoir. The dynamics of carbon storage and its release in soil are influenced by various factors, including farming practices, soil management, and environmental conditions. Specific farming systems have been observed as having a profound impact on these dynamics, potentially leading to a reduction in CO_2 emissions from the soil [19]. This phenomenon is crucial, as soils can either release carbon into the atmosphere, exacerbating greenhouse gas effects, or sequester it, thereby mitigating climate change [20–22].

The interplay between soil management practices and CO_2 emissions is a subject of growing interest. Practices such as no-tillage farming, cover cropping, crop rotation, and the use of organic amendments have been associated with increased soil organic carbon stocks and reduced CO_2 emission rates. These practices not only contribute to carbon sequestration but also enhance soil resilience—the ability of soil to maintain its functions in the face of external stresses like climate change and intensive agricultural activities [23–25].

Furthermore, there is a burgeoning recognition of the link between soil health and plant productivity. Healthy soils, rich in organic matter and with balanced nutrient cycling, provide a robust foundation for plant growth. This relationship is particularly vital in the context of global food security, as sustainable farming practices that enhance soil health can lead to more productive and resilient agricultural systems [26,27].

Crop yield is a fundamental measure of agricultural productivity and is inherently linked to soil health. The balance between maintaining high crop yields and ensuring sustainable soil management forms a critical nexus for agricultural research and policy [28–30].

The aim of this study is to elucidate the effects of various tillage practices on soil properties and crop yields; additionally, it seeks to highlight the significant potential of specific farming systems in enhancing soil organic carbon, thereby positively influencing CO_2 emissions from soil. This study contributes to the growing body of knowledge on sustainable agriculture, providing insights for farmers, agronomists, and policymakers in their quest to promote environmentally sound and productive agricultural systems.

2. Materials and Methods

2.1. Experimental Site and Management

In the experimental station of Vytautas Magnus University, Kaunas District, Lithuania (54°52′50′′ N and 23°49′41′′ E), a long-term field experiment was first established in 1999, and studies have been conducted since 2003. The soil of the experimental site is classified as Epieutric Endocalcaric Planosol (Endoclayic, Episiltic, Aric, Drainic, Endoraptic, Uterquic), according to the World Reference Base (WRB, 2022); the texture at 0–20 cm depth is moderate loamy loam (33.7% sand, 50.3% silt, 16.0% clay) and at 20–40 cm depth the texture is dusty light loam (35.4% sand, 51.1% silt, 13.5 % clay). In this study, winter oilseed rape (*Brassica napus* L.), winter wheat (*Triticum aestivum* L.), and spring barley (*Hordeum vulgare* L.) were selected for the crop rotation in the agroecosystem, as these are the predominant crops in Lithuania. The results presented in this paper were obtained in 2013, 2014, 2022, and 2023.

In the two-factor field experiment, straw (factor A) was removed (R) from one part of the experimental field, and all straw was removed from the other part of the field; the straw crop was chopped and spread (S) at harvest.

The different tillage systems were applied (factor B): (1) conventional deep plowing (CP) (control) in the autumn at 23–25 cm depth, (2) using cover crops for green manure without tillage (GMNT), and (3) abstaining from tillage (NT).

Cover crops of white mustard (*Sinapis alba* L.) for green manure were sown on GMNT-only fields immediately after harvesting winter wheat and spring barley. The main tillage operations as well as seedbed preparation—harrowing—were carried out only in the CP variants. Glyphosate (Roundup) at 4 L ha^{-1} was applied as needed in the GMNT and NT treatment fields. Rapid 300C (Väderstad, Sweden) was used in all crops, including white mustard, without any additional tillage implements until 2021. In autumn 2022, crops were sown with an Agrisem SLY BOSS (Ancenis Cedex, France) no-tillage machine. After harvesting the pre-crop (except for winter rape), the straw was removed for one-half of the experiment (R), while for the other half, the straw was chopped and spread (S). All of the tillage systems were tested in both halves of the experiment with and without straw. The design of the experiment and the farming practices are detailed in our previous article [31].

Winter wheat was fertilized with a complex fertilizer (N—120 kg ha^{-1}; P_2O—55 kg ha^{-1}; and K_2O—110 kg ha^{-1}) applied before sowing, and ammonium nitrate (N—68 kg ha^{-1}) was applied in spring. From 2001 onwards, barley was fertilized with complex fertilizers (N—50 kg ha^{-1}; P_2O 5—50 kg ha^{-1}; and K_2O ha^{-1}—50 kg ha^{-1}) before sowing and ammonium nitrate (N—30 kg ha^{-1}) after germination. For winter rape, complex fertilizers (N—44 kg ha^{-1}; P_2O 5—52 kg ha^{-1}; and K_2O—120 kg ha^{-1}) were applied before sowing, and ammonium nitrate (N—60 kg ha^{-1}) was applied after germination. Weeds and fungi in the crop were controlled using the same amount and composition of appropriate herbicides, fungicides, and insecticides in all treatments. The experiment was set up in a split-plot design with 4 replications, 48 plots in total (it had two factors, A and B). The total area of each plot was 102 (6 × 17) m^2, and the grid size was 30.0 (2.0 × 15) m^2.

2.2. Meteorological Conditions

Meteorological conditions in 2013 provided a challenging start to the year, with winter-like temperatures in early April, dropping to −7–14 °C in many regions. This extreme cold could have significantly delayed the start of the agricultural season, affecting the early stages of crop growth. However, the weather changed during the month of April, reaching 18–23 °C, although the average temperature remained 1.2 °C below the long-term average, indicating a cooler-than-normal start to the growing season [31].

The weather became warmer in May, although there were occasional frosts of −3 °C at the beginning of the month. Maximum temperatures rose to 27–31 °C, well above the historical average, and at the end of the month, the average temperature was 4 °C higher than normal. This warm spell and rainfall that was 16.5 mm above the long-term average provided favorable conditions for crop growth, although hailstorms did occur in some cases, making the climatic conditions even more difficult.

June was very warm and moderately humid, with average temperatures that were 2.9 °C above the long-term average. However, this month's below-average rainfall was 20.8 mm below the historical norm, which may have limited the crop irrigation and soil moisture levels.

The trend of warm weather continued in July, with average temperatures close to those of June and 1.6 °C above the historical average. Precipitation was above average, with particularly heavy rainfall in the second half of the month, which may have alleviated the water deficit experienced earlier.

August remained similarly warm, with average temperatures that were 1.3 °C above the long-term average. Despite a relatively dry August, rainfall was slightly below the historical norm, bringing to an end a season characterized by temperature extremes and erratic rainfall, with mixed consequences for agricultural productivity.

In 2014, conditions were favorable for sowing winter wheat, with an average temperature of +12 °C and rainfall more than twice the long-term average. These warm and humid conditions are likely to have provided optimal soil moisture and temperatures for seed germination and early growth.

Warmer weather continued to prevail in October of 2014, with average temperatures hovering around +7–7.5 °C, above the historical norm. Precipitation was below the long-term average, which may have helped to balance soil moisture levels after a wet sowing period. Temperatures in November remained above normal at an average of +4 °C, indicating a milder autumn, which may have prolonged the growing season. Precipitation was around the historical average so that soil moisture was sufficient and did not cause excessive water stress.

December was considerably warmer than the long-term average, with temperatures of around 2 °C, well above the usual −4 °C expected. These warmer temperatures and normal rainfall are likely to have been beneficial for late crop development and preparation for winter dormancy.

Early in the New Year, temperatures remained low but still typical for January, at around −5 °C, and precipitation was almost double the historical average, which may have had an impact on winter crops under snow cover. Temperatures in February were slightly above average, and precipitation slightly decreased, indicating early signs of the approach of spring.

In 2013 and 2014, meteorological conditions were highly variable, ranging from extremely cold weather to above-average temperatures, together with fluctuating rainfall. These years highlighted the challenges and opportunities for agricultural productivity that are posed by climatic conditions and underlined the importance of adaptation strategies to manage the impact of the variability in weather on agricultural activity.

In 2021, the average monthly temperatures during the growing season were below the historical averages, indicating a cooler year that could have affected the growth and development of crops. Additionally, the level of precipitation was unevenly distributed, potentially influencing water availability and soil moisture conditions critical for plant growth.

In 2022, the temperatures at the start and the end of the growing season exceeded the long-term averages, suggesting periods of higher heat that could have impacted crop development. Notably, June and August experienced significantly lower precipitation than usual, leading to a dry spell that likely hampered crop growth due to reduced water availability. During the growing season of 2023, the average monthly temperatures aligned closely with historical averages, indicating a return to normal climatic conditions. However, overall precipitation was slightly below the long-term average, suggesting a marginal decrease in precipitation but with relatively stable water conditions favorable for plant growth. These observations across different years highlight the fluctuations in weather conditions and their potential effect on agriculture. Notably, there has been a consistent trend of reduced precipitation during the growing seasons compared to long-term averages, which could have implications for soil moisture levels, water resources, and plant stress. Such conditions can influence crop yields, plant health, and the overall dynamics of agricultural systems.

This analysis underscores the importance of considering both climatic variations and their interactions with soil properties in understanding agricultural system dynamics and responses to changing weather patterns [32]. In addition, this comprehensive review is critical for assessing the impacts of climatic variability on agricultural productivity and sustainability.

2.3. Sampling and Analysis

Soil agrochemical properties. Soil sampling for the evaluation of SOC was carried out after the harvest in the autumn, after the application of the investigated measures (2003, 2013, and 2023). Soil samples were taken in each plot at a 0–10 cm and 10–25 depth of the plow layer from 15 spots. Visible roots and plant residues were removed from the soil samples by hand. Air-dried soil samples were crushed and sieved through a 2 mm sieve and homogeneously mixed. Humus and carbon contents (%) were measured using a Heraeus analyzer. Soil organic carbon stocks were then calculated as follows:

$$\text{SOC stocks} = (\text{SOC content of the soil} \times \text{soil weight})/100, \quad (1)$$

where SOC stocks are measured in t ha^{-1}; SOC content—g kg^{-1}; soil weight—Mg ha^{-1}.

A special plot harvester (Wintersteiger AG, Ried im Innkreis, Austria) was used for pre-crop harvesting. The cereal grain yield was adjusted to 14% moisture and 100% grain mass purity.

The cumulative yield differences in percentage terms compared to deep plowing in a given year are calculated according to a formula that shows the total percentage change in yield over a given period. This formula is useful in determining the long-term effects of different agricultural practices on crop yields.

$$\text{Cumulative yield difference (\%)} = (\text{Yield with deep plowing} - \text{Yield with alternative practice}/\text{Yield with deep plowing}) \times 100 \quad (2)$$

2.4. Estimation and Computation of CO_2 Emissions

Soil CO_2 emissions were measured using an infrared gas analyzer, obtaining measurements of the soil surface CO_2 efflux (µmoL m^{-2} s^{-1}). A portable, automated soil gas flux LI-8100A system with an 8100–103 chamber analyzer (LI-COR Inc., Lincoln, NE, USA) was used. In each experimental plot, in the spring, rings of 20 cm in diameter were installed into the soil, and three measurements were taken in each plot. Soil CO_2 efflux was carried out three times during the growing seasons, at the same time of day (from 10 a.m. to 1 p.m.) and fixed locations in the plot. At the start of a measurement, the LI-8100 chamber was held open above the soil collar, and the system measured the ambient soil CO_2 concentration (Cc(0)). When the chamber was closed on the soil collar, the soil CO_2 concentration in the chamber (Cc(t)) began to rise. Ignoring the dilution effect of water vapor, the rate of change in the chamber soil CO_2 concentration with time (∂Cc/∂t) was demonstrated as follows:

$$\frac{\partial Cc(t)}{\partial t} = A(Cs - Cc(t)) \quad (3)$$

where C_s is the soil CO_2 concentration (µmol mol^{-1}) in the soil surface layers, and A (s^{-1}) is a rate constant that is proportional to the CO_2 conductance at the soil surface and the surface-to-volume ratio of the chamber. If A and C_s are constant, then integration with respect to time gives the following:

$$Cc(t) = Cs + (Cc(0) - Cs)e^{-At} \quad (4)$$

In the LI-8100 system, the chamber soil CO_2 concentrations $C_c(t)$ versus time data were fitted with an exponential function of the form given in Equation (2), yielding values for the parameters A and C_s. Soil CO_2 flux was then obtained through calculation of the initial slope (∂Cc(t))/∂t from Equation (1) at time zero when the chamber touched down and $C_c(0)$ = ambient. A complete description of the equations used in the LI-8100 system, including details of dilution corrections due to water vapor, is given in the LI-8100 instruction manual.

2.5. Statistical Analysis

Experimental data were analyzed using a two-factor analysis of variance (ANOVA) based on the methodology in [33] using the SYSTAT 12 statistical software package, version 12 (SPSS Inc., Chicago, IL, USA). The significance of differences among the treatments was determined using the least significant difference (LSD) test. The inter-causality of the tested variables was estimated through the correlation–regression analysis method using STAT ENG software [34]. The probability levels indicating significant differences between specific treatments and the control treatment were denoted as follows: *—when $0.010 < p \leq 0.050$ (significant at the 95% probability level); **—when $0.001 < p \leq 0.010$ (significant at the 99% probability level); and ***—when $p \leq 0.001$ (significant at the 99.99% probability level).

3. Results

3.1. Studies on Soil CO_2 Emissions

The results of soil CO_2 emissions measured in 2013, 2014, 2022, and 2023 show differences that highlight the impact of different tillage practices and the use of cover crops on soil carbon dioxide emissions. Through the elucidation of how specific agricultural practices can mitigate or exacerbate the soil's CO_2 emissions, this study offers valuable insights into potential strategies for reducing agriculture's carbon footprint, enhancing soil health, and ultimately contributing to the global efforts against climate change. The data, therefore, stand as a critical contribution to ongoing discussions on sustainable agriculture, soil management practices, and their role in addressing environmental challenges in long-term practice.

The 2013 and 2014 data (Figures 1 and 2) show that in these years, CO_2 emissions were monitored for different tillage systems (conventional plowing (CP), green manure no-tillage (GMNT), and no-tillage (NT)) both with and without straw. These observations aimed to identify the immediate and residual impacts of tillage and straw management on soil CO_2 emissions.

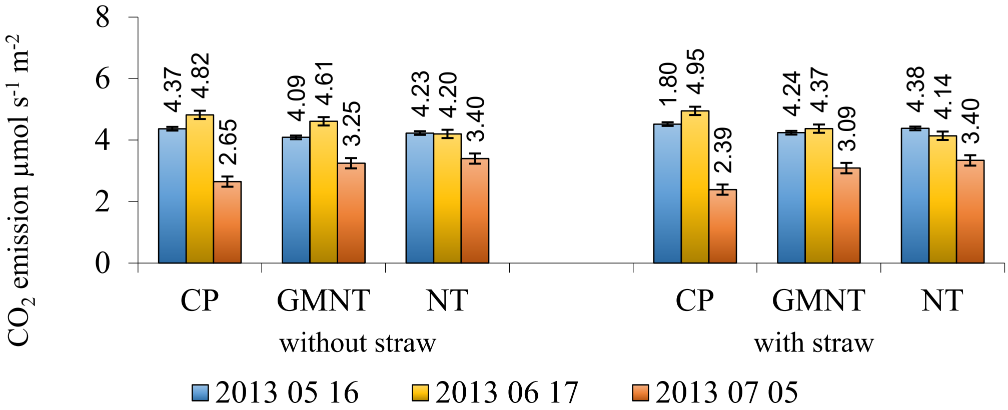

Figure 1. Soil CO_2 emissions after tillage at the beginning, middle, and end of the winter oilseed rape growing season in 2013. Note: No significant differences at $p > 0.05$; Fisher LSD test vs. control; error bars indicate the standard error. Factor A: R—straw removed (control); S—straw chopped and spread. Factor B: CP—conventional deep plowing (control); GMNT—cover cropping for green manure with no-tillage; NT—no-tillage, direct drilling.

Tillage impact, no-tillage, and green manure no-tillage practices tended to result in lower CO_2 emissions compared to conventional plowing. This suggests that minimizing soil disturbance can reduce the soil's carbon footprint in the short term. However, the differences in CO_2 emissions among the tillage practices were not consistent across all measurement periods, indicating that the impact of tillage on CO_2 emissions may vary throughout the growing season and potentially equalize over time.

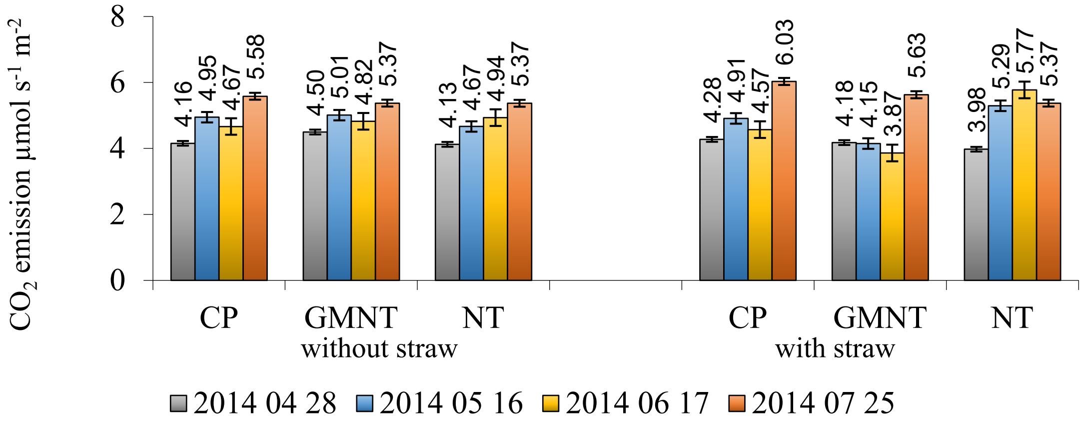

Figure 2. Soil CO_2 emissions after tillage at the beginning, middle, and end of the winter wheat growing season in 2014. Note: No significant differences at $p > 0.05$; Fisher LSD test vs. control; error bars indicate the standard error. Other explanations as in Figure 1.

Measurements taken 1 month after sowing winter oilseed rape (15 September 2021) showed that CO_2 emissions were significantly lower on the uncultivated land with cover crops and the uncultivated land with no cover crops (Figure 3). Compared to conventional deep plowing, CO_2 emissions were 29% and 28%, and 24% and 23% lower in both fields without straw and with straw, respectively. However, subsequent measurements at the beginning, middle, and end of the winter oilseed rape growing season (21 October 2021, 8 October 2022, and 25 July 2022) did not reveal any significant differences in CO_2 emissions from the soil. At that time, neither the tillage systems investigated nor the use of straw had any effect.

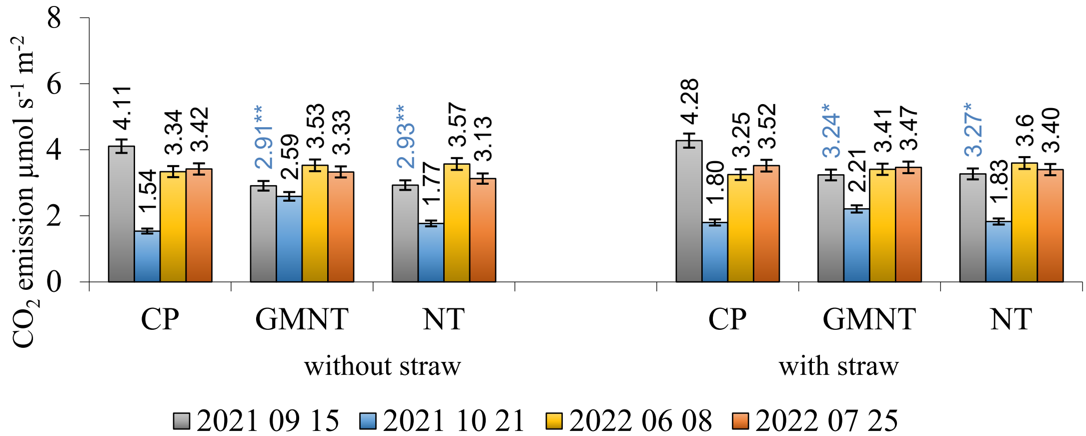

Figure 3. Soil CO_2 emissions after tillage at the beginning, middle, and end of the winter oilseed rape growing season in 2021–2022. Note: Significant differences at $^{*}0.01 < p \leq 0.05$ and ** $0.001 < p \leq 0.010$; Fisher LSD test vs. control; error bars indicate the standard error. Other explanations as in Figure 1.

In winter wheat (Figure 4), the same trends were observed at the beginning, middle, and end of the growing season as in winter oilseed rape.

Between tillage and sowing, before the soil is covered with new plants, tillage can have a significant impact on CO_2 emissions from the soil. More intensive loosening and mixing tillage practices significantly increase CO_2 emissions from the soil in the first 2 weeks compared to no tillage.

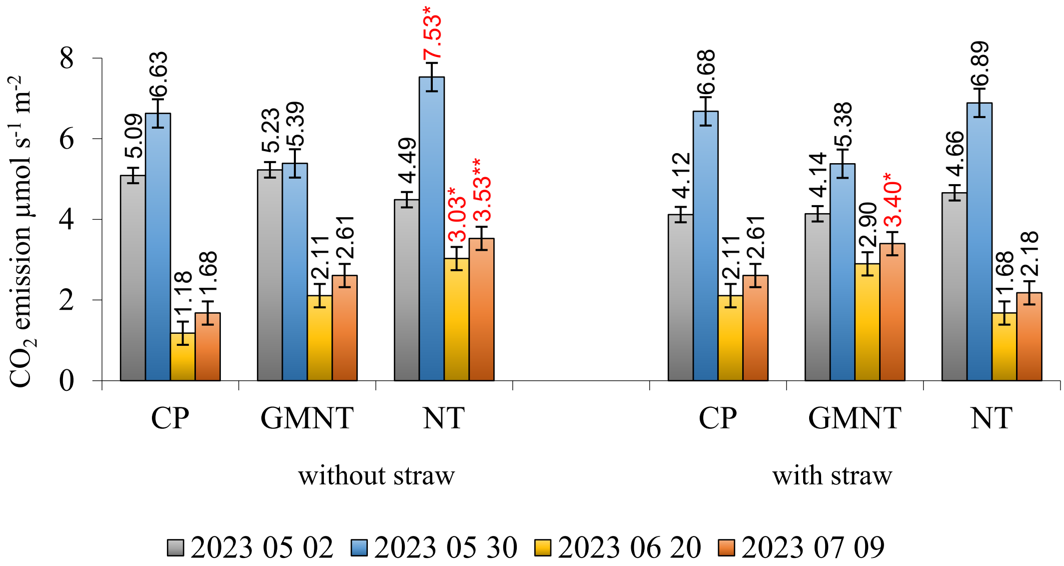

Figure 4. Soil CO_2 emissions after tillage at the beginning, middle, and end of the winter wheat growing season in 2023. Note: Significant differences at * $0.01 < p \leq 0.05$ and ** $0.001 < p \leq 0.010$; Fisher LSD test vs. control; error bars indicate the standard error. Other explanations as in Figure 1.

In relation to the changes in soil CO_2 emissions under different tillage systems and the use of straw in winter oilseed rape and winter wheat production, the results show that CO_2 emissions from the soil may vary depending on the tillage technology; however, these differences are not constant and may change throughout the plant growing season.

Direct sowing on uncultivated land, both with and without cover crops, immediately after tillage reduces the CO_2 emissions from the soil compared to conventional tillage. However, in subsequent measurements during the growing season, no significant differences in CO_2 emissions were found between the different tillage systems, indicating that the initial effect of the tillage method evens out over time.

Comparing the data from 2013 and 2014 with the projections for 2022 and 2023, it is apparent that there are yearly differences in CO_2 emissions. These differences could be attributed to variations in weather patterns, crop types, and changes in agricultural management practices over time. Understanding these annual trends is crucial for developing long-term sustainable farming strategies.

In summary, the results of this study reveal a complex interaction between tillage and plant growth on soil CO_2 emissions. Although in some cases direct sowing on uncultivated land can reduce CO_2 emissions, these effects are not the same at all stages of plant growth or under different environmental conditions. Therefore, when designing tillage strategies and applying practices that focus on sustainability and environmental protection, it is of importance to consider these contributory complex factors.

3.2. Soil Organic Carbon Stocks

Soil organic carbon (SOC) stocks in 2003, 2013, and 2023 across two soil depths (0–10 cm and 10–25 cm) and under various straw management and tillage practices reveal significant trends in SOC accumulation over 20 years (Table 1). The experimental setup included two main variables: straw management, with one practice involving the removal of straw (R) and the other involving spreading chopped straw (S), and tillage methods, which comprised conventional plowing (CP), using cover crops for green manure without tillage (GMNT), and no-tillage (NT).

Table 1. Soil organic carbon stocks in the upper and bottom plow layers, 2003, 2013, and 2023.

Factors		2003	2013	2023	2003	2013	2023
		0–10 cm Depth, t ha^{-1}			10–25 cm Depth, t ha^{-1}		
R	CP	18.20	25.89	28.6	21.30	26.80	30.8
	GMNT	23.17 *	34.41 ***	32.2 *	23.00 *	31.23 ***	33.6 *
	NT	25.15 ***	35.35 ***	36.3 ***	24.82 *	32.39 ***	32.2 *
S	CP	18.63	29.50	26.3	20.87	30.96	26.0
	GMNT	23.53 *	38.87 ***	40.8 ***	24.85 **	33.29 **	36.0 ***
	NT	25.57 ***	39.08 ***	38.1 ***	25.42 **	35.94 ***	33.6 ***

Note: Significant differences at * $0.01 < p \leq 0.05$, ** $0.001 < p \leq 0.010$, and *** $p \leq 0.001$; Fisher LSD test vs. control. Other explanations as in Figure 1.

Over the two decades, SOC stocks increased across all treatments and depths, demonstrating the soil's enhanced carbon stock potential under both improved straw management and reduced tillage practices. Specifically, the spread of chopped straw (S) resulted in a higher SOC accumulation than straw removal (R), indicating the beneficial impact of straw retention on soil carbon levels. In terms of tillage, the no-tillage (NT) and green manure no-tillage (GMNT) practices showed the most significant increase in SOC stocks, surpassing conventional plowing (CP), especially in the upper soil layer (0–10 cm). This suggests that minimizing soil disturbance and incorporating green manure are highly effective strategies for enhancing SOC.

The data presented illustrate a clear and positive evolution of soil organic carbon (SOC) stocks over two decades, highlighting the effectiveness of various straw management and tillage practices in enhancing soil carbon storage. From 2003 to 2023, an overarching trend of increasing SOC stocks was observed across all treatments and soil depths, underscoring the potential of specific agricultural practices to contribute significantly to carbon sequestration and, by extension, to climate change mitigation efforts.

One of the salient findings from the data is the positive effect of spreading chopped straw (S) on SOC accumulation compared to straw removal (R). This outcome underscores the importance of straw retention on the soil surface, which likely contributes to both protecting the soil from erosion and enhancing microbial activity that aids in the decomposition of organic matter, thereby increasing SOC stocks.

The comparison between tillage practices reveals a compelling narrative. The no-tillage (NT) and green manure no-tillage (GMNT) practices exhibited the most significant increases in SOC stocks, particularly in the upper soil layer (0–10 cm), compared to conventional plowing (CP). This trend highlights the critical role of reduced soil disturbance and the incorporation of green manures in improving soil structure, moisture retention, and microbial diversity, all of which contribute to higher rates of carbon sequestration.

Both soil depths (0–10 cm and 10–25 cm) experienced an increase in SOC stocks, with more pronounced improvements often observed in the 0–10 cm layer. This difference underscores the significance of surface soil management in carbon accumulation processes. Over the 20-year period, SOC stocks consistently rose, demonstrating the soil's enhanced capacity for carbon storage under strategic management practices. Notably, the degree of increase varied among the treatments, suggesting that a combination of straw spreading and minimal tillage practices offers the most benefit for SOC enhancement.

In conclusion, the evolution of SOC stocks over two decades clearly demonstrates the efficacy of sustainable agricultural practices in enhancing soil carbon levels. The findings advocate for the widespread adoption of strategies such as spreading chopped straw and employing no-tillage or green manure no-tillage practices. These approaches not only contribute to the significant increase in SOC stocks, thereby improving soil health and productivity, but also play a crucial role in the broader context of environmental conservation and the fight against climate change. This study serves as a compelling argument for the re-evaluation of conventional agricultural practices, urging a shift towards methods that ensure long-term sustainability and environmental stewardship.

The correlation regression analysis also showed strong correlations. In 2023, a very strong positive and statistically significant linear correlation was found in the straw-removed fields with no-tillage between the CO_2 released from the soil (12.05.2023) (r = 0.99, y = −2.464 + 2.22x, $p < 0.05$) and the soil organic carbon stock in the 0–10 cm soil layer.

3.3. Yield Stability in Agroecosystems

Sustainable agroecosystems are able to maintain their condition, yield, and biodiversity, as well as all of their integrity, over time and in the context of human activity and use. Good ecosystem health is one of the key conditions for dynamic ecosystem sustainability. Stability is closely linked to the other two elements of ecosystem sustainability—yield and biodiversity. When the links between them are weakened, ecosystem sustainability is reduced.

The sustainability of agroecosystems is thus inextricably linked to the stability of their yields. To illustrate the potential for sustainability of the tillage systems studied, the cumulative differences in percentage yield of crops grown in the experiment since the beginning of the field experiment in 2000 compared to deep plowing in that year are presented.

On uncultivated land, both with and without intercropping (IC), agroecosystem yields were significantly lower than on deep-plowed soils, even in the 11 years from the start of the experiment until 2010 (Figure 5). During this period, the sum of cumulative yield losses amounted to 79.3–92.0%. It was not until 3 years after the start of this study (2013) that the yields of the agricultural crops studied on uncultivated land started to increase slowly, and it was not until 9 years later (2022) that they were almost equal to those of deep plowing. This means that the productivity stability of these no-tillage technologies only starts to be illustrated via increased yields in the long term, 11–14 years after their introduction.

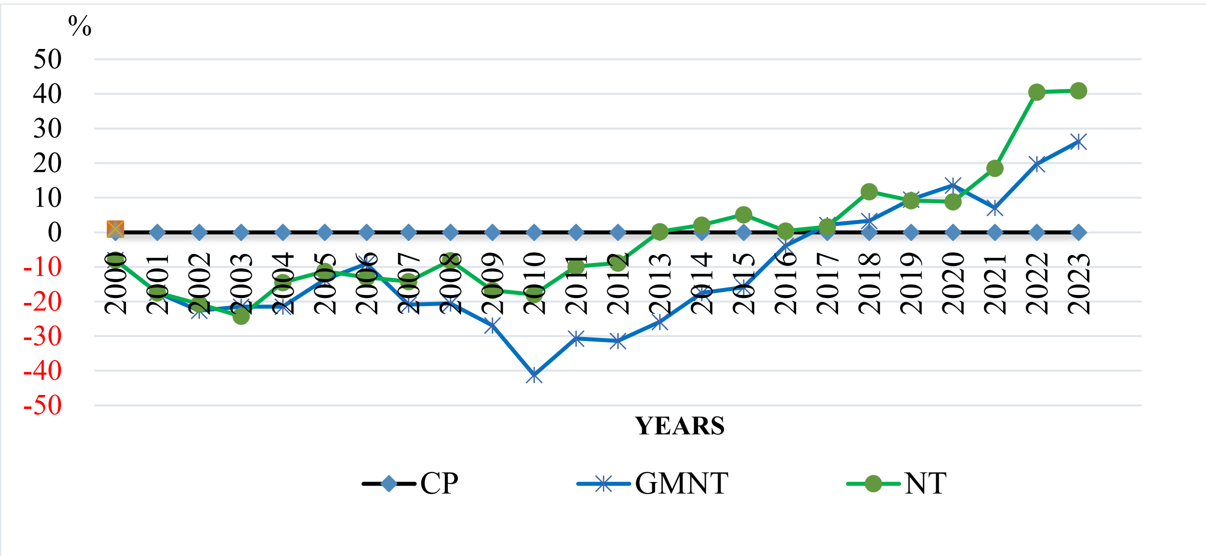

Figure 5. Cumulative differences in plant yield as a percentage compared to deep plowing in the same year, 2000–2023. Other explanations as in Figure 1.

The yield of winter wheat in 2023 depended on the organic carbon stock. Correlation regression analysis showed a moderate correlation. In the topsoil layer (0–10 cm), there was a very strong positive and statistically significant linear relationship between organic carbon stocks and the yield in 2023; r = 0.71; $p \leq 0.05$.

4. Discussion

Studies on soil CO_2 emissions are abundant around the world, but the results are highly controversial. Some authors have found similar CO_2 emissions from direct sowing, no-tillage, and conventional tillage; others have found higher CO_2 emissions from direct sowing on untilled land; meanwhile, others have argued that direct sowing on untilled land only results in higher CO_2 emissions in certain periods and lower CO_2 emissions in other periods [35,36]. Some researchers have argued that CO_2 emissions from the soil of direct sowing are generally lower compared to conventionally plowed soil for a short period after cultivation [37]. Our results are in line with those of other authors [38–40].

The increase in greenhouse gases (GHGs) in the atmosphere is primarily attributable to human activities, with agriculture playing an important role. The sector has contributed to 20% of the global greenhouse effect, and according to the IPCC, this figure has increased [41]. The significant emissions from agriculture are mainly due to practices such as the expansion of new agricultural land and the use of fossil fuels and synthetic fertilizers in conjunction with soil cultivation. As a result, much research has focused on how farming practices contribute to the increase in GHGs, especially carbon dioxide (CO_2), in the atmosphere [42–45]. Similar to our study, studies were initiated 20 years ago using different tillage systems to demonstrate the reduction in GHGs and the increase in organic carbon in soil.

Soil acts as a source of CO_2 through biochemical processes related to the activity of microorganisms and plant root respiration, which are mainly influenced by soil temperature and moisture [46–48]. The movement of CO_2 in the soil and from the soil to the atmosphere is facilitated by diffusion and mass flux, which are influenced by soil texture, structure, and moisture [48–50]. Therefore, it is essential to select and manage agricultural systems in a way that increases soil carbon stocks and reduces CO_2 emissions from soils [51–54]. The results of this study reveal the complex interactions between tillage and plant growth and soil CO_2 emissions, temperature, and moisture. Although in some cases direct sowing on uncultivated land can reduce CO_2 emissions and help to conserve soil moisture, these effects are not the same at all stages of plant growth or under different environmental conditions, as in our study, where no-tillage was applied from the start of the experimental set-up, and the organic carbon stocks increased significantly. The studies of other researchers have also suggested that the widespread adoption of low-carbon farming practices could reverse the upward trend in land-use emissions, which could substantially offset global annual emissions as projected [55–57].

The introduction of no-tillage systems is presented as a viable solution to reduce GHG emissions from agricultural activities [58–61]. Although no-tillage farming conserves soil and water reserves and reduces production costs, its soil organic carbon sequestration sub-target is dependent on the local conditions [62]. Soil organic carbon storage depends on many factors, including soil structure, drainage system, land use and cultivation, agroecosystems, and climatic conditions. A study of soil organic carbon (SOC) accumulation over 20 years under different straw management and tillage practices revealed significant trends in SOC accumulation. Practices that minimize soil disturbance and incorporate organic matter, such as no tillage and using cover crops for green manure without tillage, were shown to significantly increase SOC stocks, especially in the topsoil layer. This highlights the role of tillage management in enhancing soil carbon sequestration and shows that conservation agriculture practices can play an important role in sustainable soil health.

No tillage is identified as a sustainable agricultural practice that increases soil carbon soon after its introduction [63,64], contributing to a 0.4% increase in carbon stocks over two decades, which is in line with the strategy proposed by the United Nations [65].

The benefits of no-tillage cultivation go beyond carbon sequestration and include ecosystem benefits such as improved water and carbon storage in the soil, better biodiversity habitats, and improved nutrient availability through crop rotation and legumes, which also help to control pests and diseases and make more efficient use of water for irrigation, as well as for fertility [66,67]. Our research has shown that tillage, straw management, and plant growth interact with soil CO_2 emissions, temperature, and moisture. Although certain practices, such as direct sowing into uncultivated soil, show direct benefits in CO_2 emissions and moisture retention, these effects are not consistent across all stages of plant growth or under all environmental conditions. The significant increase in SOC with no-tillage and green manure no-tillage techniques highlights the potential of conservation agriculture for sustainable soil health and carbon sequestration [68–70]. Moreover, the specific plant responses to these techniques highlight the importance of adapted agronomic strategies to optimize yield and sustainability.

This research contributes to the knowledge base for sustainable agriculture through providing insights into practices that improve soil health and crop productivity. Finally, it contributes to the development of ecologically sustainable and productive agricultural systems, in line with the objectives of promoting organic farming and positive management of soil CO_2 emissions.

5. Conclusions

Tillage and straw management practices have a significant impact on soil CO_2 emissions, and direct sowing into uncultivated soil initially reduced CO_2 emissions. However, this initial benefit diminished over the growth cycle of the plant, indicating that the effectiveness of reduced tillage on soil CO_2 emissions varies over time. It is noteworthy that the application of no tillage and using cover crops for green manure without tillage significantly increased soil organic carbon stocks over 20 years, indicating that these measures contribute to better carbon sequestration and promote sustainable soil health. Soil temperature and moisture content appeared to be more influenced by external environmental factors than by tillage or straw management practices. In terms of crop productivity, the integration of green manure with nonagricultural practices resulted in the highest productivity in winter oilseed rape and winter wheat, although the productivity of individual crops varied and may have been influenced by other unexplored factors.

Certain farming systems can, however, increase the organic carbon content of the soil and, thus, have a positive effect on the CO_2 emissions of the soil. This finding highlights the importance of adapted agronomic practices that consider the complex interactions between tillage practices, soil properties, and plant growth to optimize yield and sustainability. Collaborative research efforts that involve farmers, scientists, policymakers, and other stakeholders are crucial for the development of holistic, practical, scalable solutions that enhance the sustainability and productivity of agricultural systems.

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