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

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

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**Abstract:** A comprehensive investigation was undertaken at Vytautas Magnus University Experimental Station, located at 54°52′50″ N latitude and 23°49′41″ E longitude on soil (*Epieutric Endocalcaric Planosol* – PLe-gln-w) since 1999, to understand the impacts of different agrotechnical measures on soil health and crop yield. 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 ploughing, shallow ploughing, ploughless tillage, single seedbed discing, and two no-tillage practices, one of which involved cover crops. Findings from this long-term study highlight the significant potential of specific farming systems in enhancing soil organic carbon. It has a positive effect on the release of $CO_2$ emissions from the soil, thus promoting soil resilience and increasing plant productivity. These insights are paramount in devising sustainable agricultural strategies to counter the challenges of climate change on agroecosystems. This research showcases the profound effects of combining residue management and tillage practices, setting a novel standard for sustainable soil management of climatic uncertainties.

**Keywords:** Soil Organic Carbon; $CO_2$ Emissions; Soil Resilience; Crop Yield; Sustainable Agriculture

## 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, focusing on conventional deep ploughing, shallow ploughing, ploughless 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. Primarily centres on how soil tillage systems practices influence soil organic carbon (SOC) levels and subsequent carbon dioxide (CO2) 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, understanding the dynamics of SOC under different tillage regimes is vital [13,14]. The critical role of agriculture in

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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 release in soil are influenced by various factors, including farming practices, soil management, and environmental conditions. Specific farming systems have been observed to have 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-till 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. 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, a long-term field experiment has been established since 1999. 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 of the topsoil is sandy loam, and the agrochemical properties are the following: $pH_{KCl}$ – 7.6 (slightly alkaline), plant-available potassium ($K_2O$) – 134 mg $kg^{-1}$ and phosphorus ($P_2O_5$) – 266 mg $kg^{-1}$ [31].

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 experiment, based on two factors, assessed the impact of straw management (Factor A) where in one section of the field straw was removed in spring barley (R), and in another, the straw was chopped and spread (S) at harvest time. The investigation also explored three tillage methods as subplots: (1) conventional deep ploughing (CP) in the autumn at 23–25 cm depth; (2) using cover crops for green manure without tillage (GMNT); and (3) abstaining from tillage (NT). These tillage methods were applied across both sections of the field, with and without straw management. The conventionally ploughed plots were tilled with disc implements

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and ploughed deeply in the autumn. In the GMNT plots, white mustard (Sinapis alba L.) was sown as a green manure cover crop on stubble right after the harvest of winter wheat and spring barley.

In 2021, the crops were sown with a Väderstad pneumatic no-tillage machine; in autumn 2022, crops were sown with an Agrisem SLY BOSS no-tillage machine. Following the harvest of the preceding crop (excluding winter oilseed rape), straw was either removed from half of the experimental area (R) or chopped and spread across the other half (S). This methodology, along with the agricultural practices employed, has been elaborated upon in our prior publication.

### *2.2. Meteorological Conditions*

In 2021, the average monthly temperatures (Table 1) 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 (Table 2), 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 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 favourable for plant growth. These observations across different years highlight the fluctuation in weather conditions and their potential effects 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.

The 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]. This comprehensive view is critical for assessing the impacts of climatic variability on agricultural productivity and sustainability.

**Table 1.** Average temperature (°C) and the sum of active temperatures (SAT) during the growing seasons of 2021, 2022, and 2023, measured at Kaunas Meteorological Station.

| Year/Month | 04 | 05 | 06 | 07 | 08 | SAT |
|---|---|---|---|---|---|---|
| 2021 | 6.1 | 12.3 | 15.6 | 17.6 | 16.6 | 1675.6 |
| 2022 | 7.1 | 11.4 | 15.4 | 17.4 | 20.3 | 1800.2 |
| 2023 | 9.1 | 13.0 | 19.8 | 17.1 | 18.1 | 1918.5 |
| Long-term average, 1974–2023 | 6.9 | 13.2 | 16.1 | 18.7 | 17.3 | - |

SAT, sum of active temperatures (≥10 °C).

**Table 2.** Precipitation (mm) during the growing seasons of 2021, 2022, and 2023, measured at Kaunas Meteorological Station.

| Year/Month | 04 | 05 | 06 | 07 | 08 | Sum |
|---|---|---|---|---|---|---|
| 2021 | 56.5 | 63.8 | 45.9 | 118.5 | 67.2 | 351.9 |
| 2022 | 46.0 | 43.8 | 16.4 | 72.4 | 6.9 | 185.5 |
| 2023 | 0.6 | 29.9 | 49.4 | 60.1 | 68.2 | 208.2 |
| Long-term average, 1974–2023 | 41.3 | 61.7 | 76.9 | 96.6 | 88.9 | 365.4 |

### *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 and 2023). Soil samples were taken in each plot at a 0–10 cm depth of the plough layer from 15 spots. Visible roots

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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 analyser. Soil organic carbon stocks were then calculated as follows:

(1) SOC stocks = (SOC content of the soil × soil weight)/100,

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. Cereal grain yield was adjusted to 14% moisture and 100% grain mass purity.

### *2.4. Estimation and Computation of $CO_2$ Emissions*

Soil $CO_2$ emissions were measured using an infrared gas analyser, 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 analyser (LI-COR Inc. USA) was used. In each experimental plot, in spring, rings of 20 cm in diameter were installed into the soil, and three measurements were made 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 vapour, the rate of change in chamber soil CO2 concentration with time (∂Cc/∂t) was given by:

$$(2)\ \frac{\partial Cc(t)}{\partial t} = A(Cs - Cc(t))$$

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:

$$(3)\ Cc(t) = Cs + (Cc(0) - Cs)e^{-At}$$

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 by calculating 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 vapour, is given in the LI-8100 Instruction Manual.

### *2.5. Statistical Analysis*

Experimental data were analysed using a two-factor analysis of variance (ANOVA) based on the methodology in [33] using the SYSTAT 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 are 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, Moisture and Temperature*

Studies on soil $CO_2$ emissions are abundant around the world, but the results are highly controversial. Some authors find similar $CO_2$ emissions from direct sowing, no-till and conventional tillage, others find higher $CO_2$ emissions from direct sowing on untilled land, while others argue 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 argue that $CO_2$ emissions from the soils of direct sowing are generally lower compared to conventionally ploughed soils for a short period after cultivation [37].

Measurements taken 1 month after sowing winter oilseed rape (15.09.2021) showed that $CO_2$ emissions were significantly lower on uncultivated land with cover crops and uncultivated land with no cover crops (Figure 1). Compared to conventional deep ploughing, $CO_2$ 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 (21.10.2021, 8.10.2022 and 25.7.2022) 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.

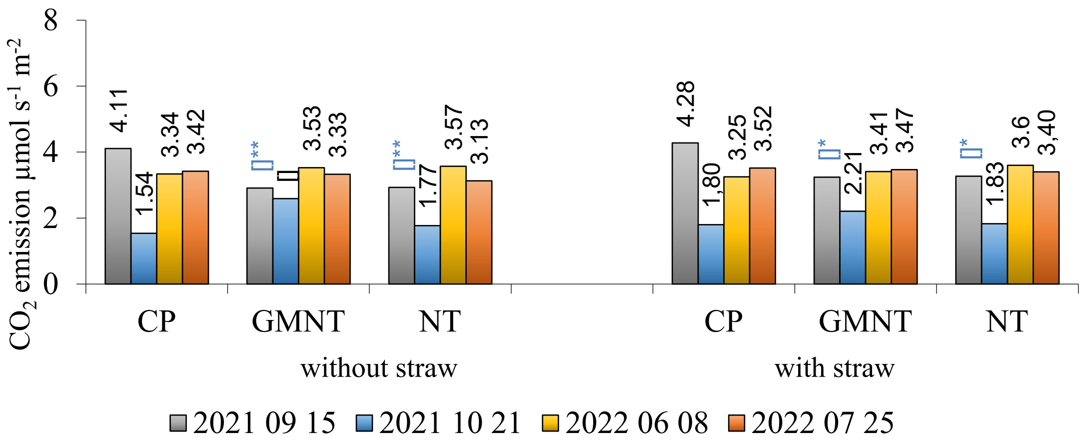


**Figure 1.** Soil $CO_2$ emissions after tillage at the beginning, middle and end of the winter oilseed rape growing season 2021-2022. Notes. Significant differences at *P ≤0.05>0.01; **P ≤ 0.010 > 0.001; *** P ≤ 0.001; Fisher LSD test vs. control. Factor A: R - straw removed (control), S – straw chopped and spread. Factor B: CP - conventional deep ploughing (control), GMNT – cover cropping for green manure with no-till, NT - no-tillage, direct drilling.

In winter wheat (Figure 2), the same trends were observed at the beginning, middle and end of the growing season as in winter oilseed rape.

Our results are in line with those of other authors [38,39]. 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.

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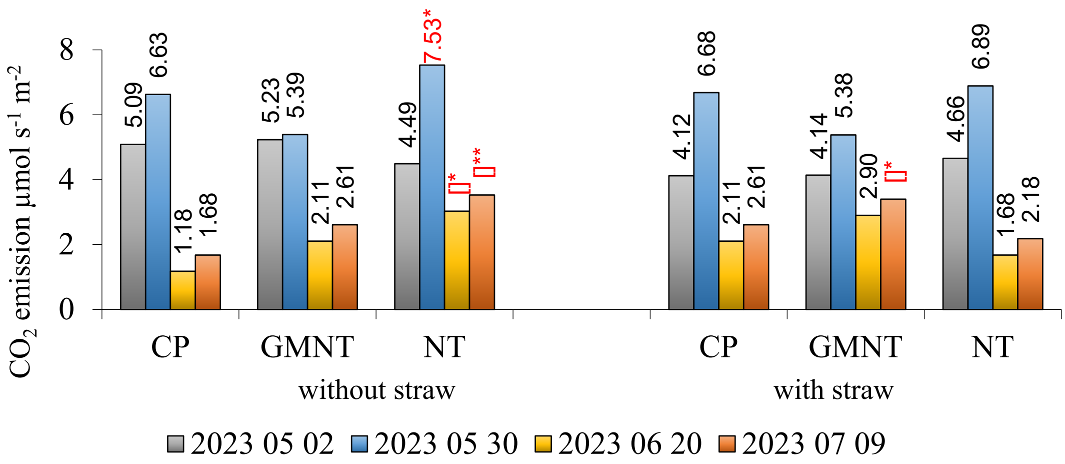


**Figure 2.** Soil CO₂ emissions after tillage at the beginning, middle and end of the winter wheat growing season in 2023. Notes. Significant differences at *$P$ ≤0.05>0.01; **$P$ ≤ 0.010 > 0.001; Fisher LSD test vs. control. Other explanations as in Figure 1.

The thermal exchange process in the soil depends on meteorological conditions, the thermal conductivity of the soil, the thermal capacity, the water content of the soil and other soil properties. One of the main factors influencing the thermal process of the soil is tillage and the covering of the soil surface with various plants or their residues. However, in our field experiment, the temperature of the topsoil was not significantly influenced by the tillage system studied or using straw (Figures 3 and 4).

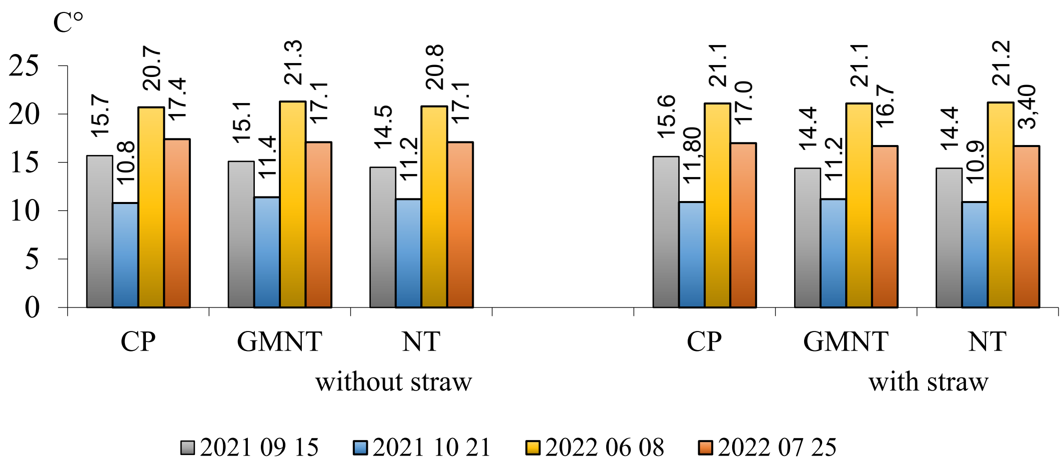


**Figure 3.** Soil temperature in winter oilseed rape after tillage, at the beginning, middle and end of the growing season, 2021-2022. Notes. No significant differences at $P > 0.05$; Fisher LSD test vs. control. Other explanations as in Figure 1.

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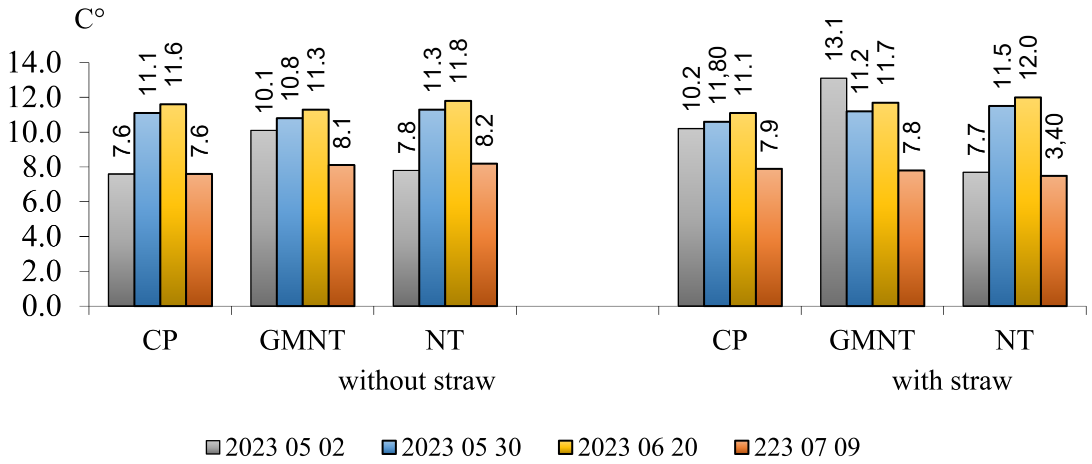


**Figure 4.** Soil temperature of winter wheat after tillage, at the beginning, middle and end of the growing season, 2023. Notes. No significant differences at $P > 0.05$; Fisher LSD test vs. control. Other explanations as in Figure 1.

Soil moisture conservation is becoming increasingly important in a changing climate. Under dry conditions, direct sowing into uncultivated land allows better moisture retention in the 0–10 cm soil layer and is considered a moisture-saving measure [40]. However, under the 2022–2023 meteorological conditions, neither the tillage systems studied nor the use of straw had a significant impact on the soil moisture content in the surface layer (Figures 5 and 6).

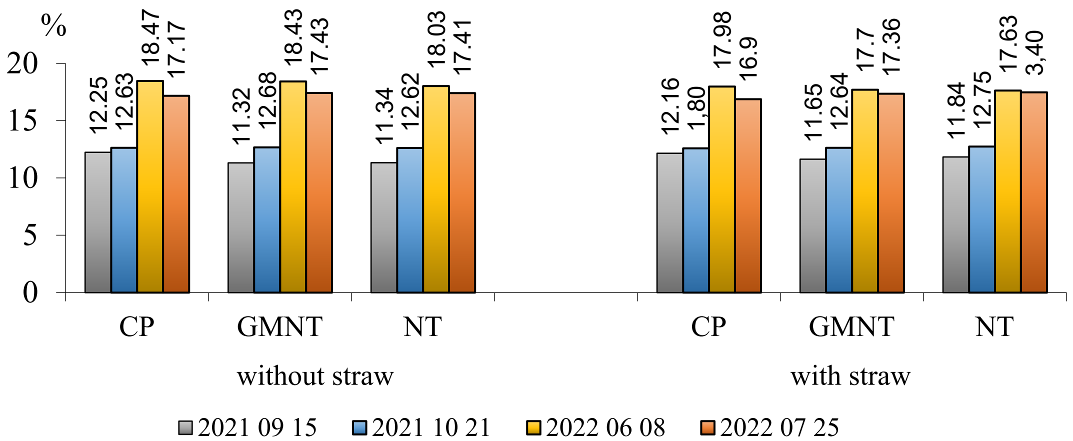


**Figure 5.** Soil moisture content after tillage at the beginning, middle and end of the winter oilseed rape growing season 2021-2022. Notes. No significant differences at $P > 0.05$; Fisher LSD test vs. control. Other explanations as in Figure 1.

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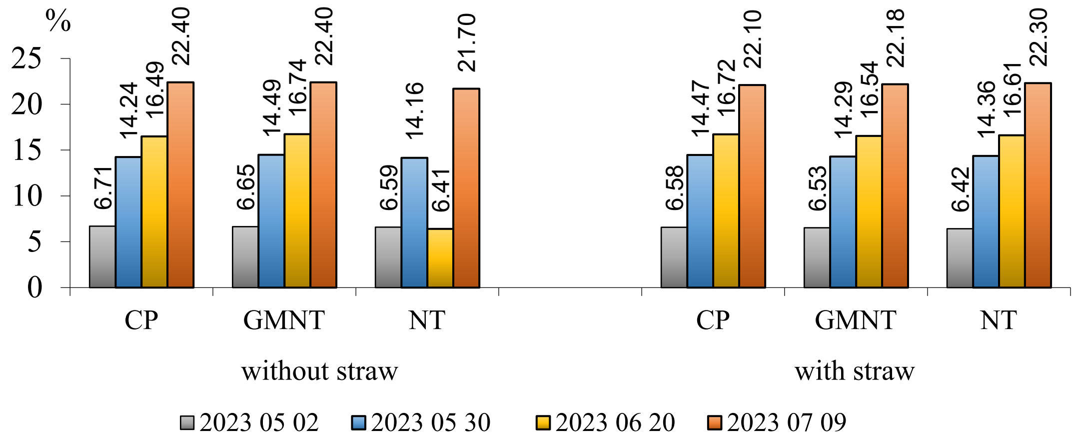


**Figure 6.** Soil moisture content after tillage at the beginning, middle and end of the winter wheat growing season in 2023. Notes. No significant differences at $P > 0.05$; Fisher LSD test vs. control. Other explanations as in Figure 1.

Changes in soil $CO_2$ emissions, temperature and moisture 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, but that 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 $CO_2$ 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.

Soil temperature was not found to be significantly influenced by tillage system or straw application. This suggests that soil temperature is more dependent on other factors, such as meteorological conditions, rather than directly on the tillage method.

A very important aspect is soil moisture retention, which is particularly important in arid conditions. Although direct sowing on uncultivated land has traditionally been considered a moisture conserving measure, this study found that, under specific meteorological conditions, the use of different tillage systems or straw did not have a significant impact on soil moisture content.

In summary, the results of the study reveal a complex interaction between tillage and plant growth on 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. It is therefore important to consider complex factors when designing tillage strategies and applying practices that focus on sustainability and environmental protection.

### *3.2. Soil Organic Carbon Stocks*

Soil organic carbon (SOC) stocks in 2003 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 3). 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 ploughing (CP), using cover crops for green manure without tillage (GMNT), and no-tillage (NT).

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 higher SOC accumulation

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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 ploughing (CP), especially in the upper soil layer (0–10 cm). This suggests that minimising soil disturbance and incorporating green manure are highly effective strategies for enhancing SOC.

**Table 3.** Soil organic carbon stocks in the upper and bottom plough layers, 2003 and 2023.

| Factors | | 2003 | 2023 | 2003 | 2023 |
|---|---|---|---|---|---|
| | | 0–10 cm depth, t ha$^{-1}$ | | 10–25 cm depth, t ha$^{-1}$ | |
| **A** | R | 20.67 | 32.34 | 21.30 | 31.08 |
| | S | 22.17 | 35.06* | 23.00 | 31.87 |
| **B** | CP | 18.63 | 27.43 | 20.87 | 28.87 |
| | GMNT | 23.53* | 36.49*** | 24.85** | 33.84*** |
| | NT | 25.57*** | 37.17*** | 25.42** | 31.71** |

Notes. Significant differences at *P ≤0.05>0.01; **P ≤ 0.010 > 0.001; *** P ≤ 0.001; Fisher LSD test vs. control. Other explanations as in Figure 1.

After 20 years, the increase in SOC was most pronounced under the no-tillage (NT) and green manure no-tillage (GMNT) methods, with the NT method showing the highest increase in the upper soil layer (from an initial 25.57 t ha$^{-1}$ to 37.17 t ha$^{-1}$). Similarly, the GMNT method demonstrated a substantial increase, reaching 36.49 t ha$^{-1}$ from an initial 23.53 t ha$^{-1}$ in the upper soil layer. These changes underscore the critical role of tillage management in soil carbon dynamics and highlight the potential of conservation agriculture practices for sustainable soil health and carbon sequestration.

The correlation regression analysis showed to strong correlations. In 2023, a linear very strong positive and statistically significant correlation was found in the straw-removed fields with no-till between the $CO_2$ release 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. Crop Yields for Winter Oilseed Rape and Wheat*

The experimental data examines the impact of straw management and tillage methods on the productivity of winter oilseed rape in 2022 and winter wheat in 2023.

In winter oilseed rape in 2022 (Figure 7), the use of green manure and no-tillage (GMNT) method yielded the highest productivity regardless of straw management, with a peak productivity of 3.52 t ha$^{-1}$ when the straw was incorporated. This suggests a synergistic effect of green manure and conservation tillage practices on oilseed rape yield. In contrast, traditional deep ploughing (CP) had the lowest yield when straw was removed, although yields substantially improved with the incorporation of straw.

For winter wheat in 2023, the trends were slightly different. The highest yields were observed with the GMNT method without straw and with the CP method when straw was incorporated. This indicates that while green manure and no-tillage practices are generally beneficial, the incorporation of straw can offset the lower yields associated with traditional ploughing, possibly due to the added organic matter and nutrients.

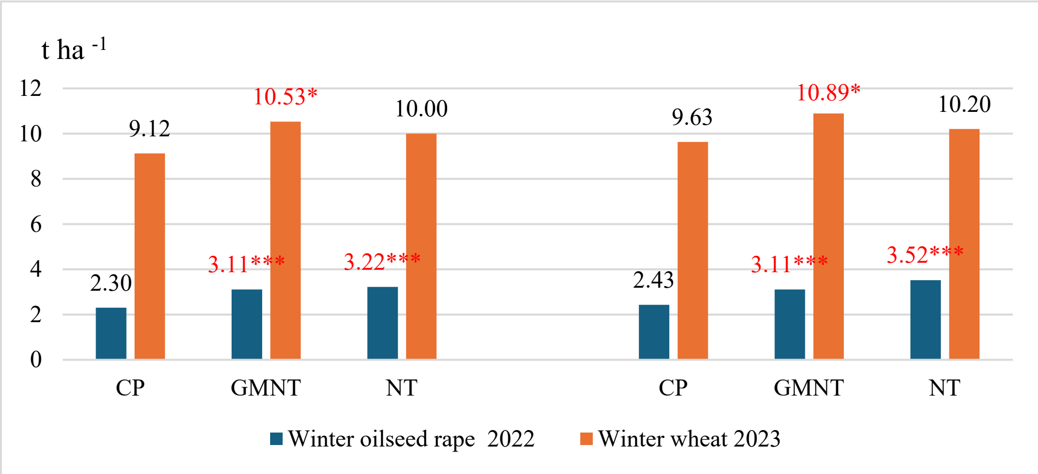


**Figure 7.** Yields for winter rapeseed in 2022 and winter wheat in 2023 **Notes.** Significant differences at *P ≤0.05>0.01; **P ≤ 0.010 > 0.001; *** P ≤ 0.001; Fisher LSD test vs. control. Other explanations as in Figure 1.

The data suggests that integrating green manure with no-tillage is generally the most productive practice for both crops, with straw incorporation offering additional benefits in certain cases. However, the variation in response between the two crops suggests that the effectiveness of these methods is crop-specific and may depend on other environmental and management factors not detailed in the experiment. The results underscore the importance of adopting tailored agronomic practices for different crops to optimize yield and potentially enhance sustainability.

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

## 4. Discussion

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 fertilisers in conjunction with soil cultivation. As a result, much research has focused on how farming practices contribute to the increase of GHGs, especially carbon dioxide ($CO_2$), in the atmosphere [42–45]. Like ours, studies started 20 years ago using different tillage systems to demonstrate the reduction of GHGs and the increase of 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]. It is therefore 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, the organic carbon stocks increased significantly. Studies by other researchers also suggest 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].

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The introduction of no-tillage systems is presented as a viable solution to reduce GHG emissions from agricultural activities [58–61]. Although no-till farming conserves soil and water reserves and reduces production costs, its soil organic carbon sequestration sub-target depends on 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 minimise 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-till 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-till and green manure no-till 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 optimise yield and sustainability.

The research contributes to the knowledge base for sustainable agriculture by 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 diminishes 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 non-agricultural 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 soil $CO_2$ emissions. It highlights the importance of adapted agronomic practices that consider the complex interactions between tillage practices, soil properties and plant growth to optimise yield and sustainability. The conclusions provide valuable insights for farmers, agronomists and policymakers seeking to promote ecological and productive agricultural systems, thus making a significant contribution to the body of knowledge on sustainable agriculture.

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