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The influence of agricultural tillage practices on soil carbon sequestration

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Abstract: Agricultural activity historically and currently contributes to climate change. Significant changes in crop technology are needed to mitigate climate change by reducing CO_2 emissions and increasing carbon sequestration in soil. The aim of the research was to determine the impact of different agricultural methods on carbon sequestration in the soil and, consequently, on the climate. The effects of conventional and two conservation cultivation methods, no-till and strip-till, on soil properties were examined from a climate change perspective. Studies have shown that reduced tillage systems, especially no-till, contributed to increased total organic carbon (TOC) and organic carbon lability (*L*) in the soil compared to conventional methods, suggesting that they may contribute to climate change mitigation and soil quality improvement. The type of crop in this system influenced the TOC level and increased as follows: sugar beet < maize < winter wheat < winter rape. Soil quality indices: the carbon pool index (*CPI*), the carbon management index (*CMI*) and the lability index (*LI*) exhibited similar patterns to those observed for TOC and *L*. Higher values of these indicators in no-till (NT) and strep-till (ST) systems than in conventional cropping confirm the advantages of conservation agriculture in terms of improving soil condition and increasing carbon storage.

Keywords: agriculture, carbon (C) sequestration, climate change, crop systems, tillage practices

INTRODUCTION

Increasing changes in the Earth's climate have led to an intensification of global climate agreements. A key milestone in this process was the 2015 UN Climate Change Conference (UNFCCC, 2015), which took place in Paris, France. The conference's primary conclusion was the urgent need to reduce CO_2 emissions to keep the global temperature rise below 1.5°C above pre-industrial levels. Increasing carbon (*C*) accumulation in agricultural soils can significantly contribute to achieving the goal of the Paris Climate Conference (Kreibich, 2014; IPCC, 2018; Fawzy *et al*., 2020; Tanneberger *et al*., 2021). Currently, the global average temperature is approaching the 1.5°C threshold recommended by the Paris Agreement. Therefore, it is crucial to immediately reduce CO_2 and other greenhouse gas emissions to mitigate the predicted catastrophic consequences for our civilisation (Theodoridis *et al*., 2020; IPCC, 2021; Ljungqvist, Seim and Collet, 2024; Lenz, 2025).

Increasing C content ("sequestration") in soil is an important role for agriculture in mitigating climate change. In the literature, the term "C sequestration" is defined differently. In our work, we adopt the following definition: 'The process of transferring CO_2 from the atmosphere to the soil of a terrestrial unit via the unit's plants, plant residues and other organic solids that are stored or retained within the unit as part of the soil organic matter (*SOM*) (Ohio State University Extension).

Sequestration of soil organic carbon (*SOC*) should result in an increase in net SOC storage surpassing the pre-cultivation baseline level (Lal, 2008; Olson *et al*., 2014; Don *et al*., 2024).

Sequestration, or the storage of C in soils, is the result of two opposing processes: the accumulation of C and its loss through CO_2 emissions (Shahzad *et al*., 2022). Soil C sequestration variability is a key factor influencing climate change. Whether this process leads to emission or storage depends on many factors and depends on many factors and has not yet been fully calculated. Due to the complexity and variability of soil structures, the rate at which C is decomposed and released varies with depth and temperature. While some C may be released rapidly, other portions may remain sequestered for hundreds of years (Nieder, Benbi and Isermann, 2024). Over millennia of agricultural use, the C stocks in approximately 50% of the world's soils, to a depth of one metre, have been disturbed, releasing some of the stored C into the atmosphere. Conventional mineralisation contributes to its stabilisation and long-term removal from the soil. However, a significant proportion of conventional has a short turnover cycle and returns to the atmosphere as CO_2. The conversion of conventional into stable mineralised forms is generally a much slower process (Dignac, 2017; Bailey, Pries and Lajtha, 2019; Basile-Doelsch, Balesdent and Pellerin, 2020).

Several methods can increase C uptake from the atmosphere into the soil (Minasny *et al*., 2017; Chenu *et al*., 2019; Szymański, Bartos and Klimek, 2021; Liu *et al*., 2024), including:
- implementing no-till and agroforestry cropping systems;
- introducing deep-rooted crops, such as certain energy crops;
- expanding forests, grasslands and wetlands at the expense of agricultural land;
- preventing soil erosion.

Implementing negative emission technologies (NETs) can stabilise the Earth's climate while providing additional environmental benefits. Their primary function is to remove CO_2 from the atmosphere and ensure its permanent storage (carbon dioxide sequestration), with the ultimate goal of offsetting anthropogenic CO_2 emissions and achieving net negative global emissions (IPCC, 2018; Beerling *et al*., 2020; Adun *et al*., 2024; Bednar *et al*., 2024). However, the cost of financing NETs may limit the fiscal resources available for a socially inclusive transition (Johnson *et al*., 2020; Otto *et al*., 2021; Andreoni, Emmerling and Tavoni, 2024).

Two key approaches to climate change mitigation are (Bednar *et al*., 2024):
(i) natural climate solutions (*NCS*), which use ecosystems to absorb and store CO_2;
(ii) reducing greenhouse gas emissions from energy, industry, and transport.

There is no scientific consensus on the effectiveness of NCS in mitigating climate change. While some studies are optimistic about its effectiveness (Griscom *et al*., 2020), others are more sceptical (Santos, Gonçalves and Pires, 2019). However, there is a general consensus that NCS alone is not enough to effectively mitigate climate change (Bednar *et al*., 2021), and it should be considered a supplementary approach to achieving climate goals (Pires, 2019). Therefore, a significant reduction in greenhouse gas emissions from the energy and industrial sectors is necessary (Worrell *et al*., 2018).

The definition of conservation agriculture (*CA*) is based on three basic principles (Derpsch *et al*., 2014; Kassam, Friedrich and Derpsch, 2019; Cordeau, 2024):
(i) permanent soil cover with crops or crop residues;
(ii) minimal disturbance of soil structure;
(iii) crop diversification through rotation and cover crop mixtures.

Assessing the impact of agriculture on current climate change is, apart from increasing food production, an extremely important issue. Brovkin *et al*. (2019) and Murphy (2024) estimate that agriculture has contributed approximately 25% of historical human-induced CO_2 emissions over the past two centuries. Over the past 60 years, global agriculture has undergone revolutionary changes, including the green revolution. This has significantly increased crop yields but has also contributed to rising atmospheric CO_2 concentrations (Bailey-Serres *et al*., 2019). Agriculture currently accounts for 10–12% of global CO_2 emissions (Nsabiyeze *et al*., 2024). However, its share decreased slightly between 1992 and 2020 from 11.4 to 10.9 Pg CO_2eq probably due to reduced deforestation, despite the increased use of nitrogen fertilisers, irrigation, and removal crop residues (Li *et al*., 2025).

Sadatshojaei, Wood and Rahimpour (2021), as well as Budai *et al*. (2024), identified straightforward methods of increasing soil C content. These include converting croplands and pastures into forests and wetlands, and growing fast-growing, deep-rooted energy crops such as miscanthus (*Miscanthus* sp.) and switchgrass (*Panicum virgatum*). However, conventional tillage methods generally reduce SOC by breaking up soil aggregates, accelerating the decomposition of organic matter, and promoting erosion (Mehra *et al*., 2018; Abbas *et al*., 2020; Colunga *et al*., 2025).

In terms of mitigating or stabilising climate change, adopting new systems such as reduced-crop agriculture offers hope of transforming agriculture, which is currently one of the factors contributing to climate change. These methods, also known as conservation tillage or direct drilling, involve minimal soil disturbance and the partial mixing of residues with the soil, resulting in indirect improvements to soil quality (Reicosky, 2015; Blanco-Canqui and Wortmann, 2020). Various CA techniques have been described in the literature, including no-till (NT), strip tillage, ridge tillage, deep tillage, and mulching. However, these methods are not always clearly defined, highlighting the need for standardised methodology and nomenclature (Derpsch *et al*., 2014; Cordeau, 2024). Nevertheless, any new agricultural practices aimed at mitigating climate change must not reduce global food production. Food shortages would discourage the adoption of climate-smart agricultural practices that reduce crop yields (Wheeler and Braun von, 2013; Fujimori *et al*., 2019).

The Food and Agriculture Organization (FAO, 2016) defines Conservation Agriculture as: 'a farming system that aims to protect, improve, and use natural resources more efficiently through the integrated management of soil, water, and biological resources, in combination with external inputs. It contributes to environmental protection as well as sustainable agricultural production.' A major challenge in analysing research is the lack of standardised terminology. The definitions of basic farming systems vary widely and many studies fail to accurately classify the farming practices they evaluate (Derpsch *et al*., 2014; Meuwissen *et al*., 2019; Behera and France, 2023).

Despite its environmental benefits, conservation agriculture currently accounts for only 12.5% of the world's arable land (Kassam, Friedrich and Derpsch, 2019). Among conservation methods, NT is the least intrusive to soil ecosystems, as it involves placing seeds directly into a narrow slit or hole that is then covered without any additional cultivation (Derpsch *et al*., 2014). A key question in modern agriculture is whether, despite its environmental benefits, NT leads to lower yields than conventional agriculture. The conclusions from research on this issue remain ambiguous, as agricultural productivity depends not only on farming practices, but also on local environmental and climatic conditions. Given this complexity, it is difficult to justify universal recommendations regarding the impact of conservation tillage on yields (Knapp and Heijden van der, 2018).

A review of the scientific literature generally indicates that reducing crop interference often leads to lower yields (Rusinamhodzi *et al*., 2011; Soane *et al*., 2012; Lal, 2015; Ernst *et al*., 2016; Ernst *et al*., 2020; Sun *et al*., 2020; Wittwer *et al*., 2021). Studies by Pittelkow *et al.* (2015) and Putte van den *et al.* (2016), for example, estimate this reduction to be around 3–5% on average. However, some regions report much higher losses. For instance, Känkänen *et al*. (2011) found yield reductions of 20% for oats, 30% for wheat, and 37% for barley in Finland. Similarly, Orzech *et al*. (2011) documented a drastic 63% reduction in spring barley yields in no-till systems in Poland.

Contary, numerous studies suggest that conservation tillage can increase yields compared to conventional methods (Kopittke *et al*., 2019; Francaviglia, Almagro and Vicente-Vicente, 2023; Sadiq *et al*., 2024). Furthermore, some studies show no significant difference between tillage methods and crop productivity (Knapp and Heijden van der, 2018; Chabert and Sarthou, 2020; Morugán-Coronado *et al*., 2020). Page, Dang and Dalal (2020), as well as Ernst *et al.* (2020), emphasise that the impact of reduced tillage on yields depends on local conditions and can result in either an increase or a decrease. This variation highlights the complexity of agricultural productivity, which depends on factors such as soil conditions, climate, crop type, and the quality of technologies employed. Therefore, it remains difficult to make a final assessment of the impact of new cultivation technologies on yields.

Reducing greenhouse gas emissions is a key goal of climate change mitigation, and C sequestration in agricultural soils plays an important role in this proces. Conventional agriculture, characterised by mechanical tillage, contributes significantly to soil gradation. The centuries-old use of this cultivation method results primarily in the loss of SOC. Equally unfavourable are other effects on soil properties, such as: reduction of nutrients such as nitrogen, structural changes consisting primarily in the degradation of soil aggregates, reduction of biodiversity, and hydrological disturbances (Jugović, Ponjičan and Jakišić, 2020; Hussain *et al*., 2021; He *et al*., 2022; Tobiašová *et al*., 2023).

There is a need to intensify scientific research on unconventional agricultural practices that enhance soil C sequestration. New cultivation methods such as conservation agriculture, and especially no-till, give rise to hope that their implementation will contribute to halting the unfavourable changes in the environment caused by conventional agriculture.

Based on the results of several studies (Pittelkow *et al*., 2015; Andruszczak, 2017; Chabert and Sarthou, 2020; Page, Dang and Dalal, 2020; Vista, Gaihre end Dahal, 2024; Jug *et al*., 2025), the main benefits of conservative cultivation methods are:

- increased soil organic C content, leading to improved soil structure and reduced atmospheric CO_2 levels (this property is not clear and is discussed below);
- increased nutrient availability and water retention, improving overall soil fertility;
- increased soil structural stability, significantly higher than in conventional agriculture;
- reduced soil erosion and surface water runoff, reducing the risk of land degradation;
- increased soil biological activity, promoting healthier ecosystems;
- reduced labour costs, machinery wear and fossil fuel consumption, making CA more energy efficient.

Despite its benefits, CA also poses some challenges:

- lower crop yields (as reported in most studies);
- increased herbicide use, leading to potential ecotoxicological risks;
- increased N_2O emissions, which may counteract some of the climate benefits;
- soil acidification, reducing nutrient availability for crops.

These advantages and disadvantages highlight the complexity of CA implementation issues and the need for regional research to maximise the benefits of this method while minimising its drawbacks.

Increasing C sequestration in soil is a significant challenge for new cultivation technologies. Analysis of the literature on the subject does not provide a clear answer regarding the generally beneficial impact of simplified cultivation methods on climate protection. Significantly higher C sequestration in the 0–10 cm surface layers of NT than CT is reported in virtually all publications (e.g., West and Post, 2002; Luo, Wang and Sun, 2010; Padbhushan *et al*., 2024), as is the case in the 0–30 cm layer (e.g., Zhao *et al*., 2015; Bohoussou *et al*., 2022; Tadiello *et al*., 2023). In the 10–30 cm layers, the results of analyses indicate no effect of the cultivation method on C sequestration (Chen *et al*., 2011; Du *et al*., 2017; Hashimi, Kaneko and Komatsuzaki, 2023) or higher sequestration in the conventional method (Angers and Eriksen-Hamel, 2008; Tadiello *et al*., 2023; Colunga *et al*., 2025). In the lower horizons, this differentiation between cultivation methods is even greater. In summary, although the effect of NT is clearly beneficial for soil characteristics, the effect on C sequestration is not unequivocally positive.

MATERIALS AND METHODS

RESEARCH OBJECTIVE

The overall aim of the study was to assess the impact of agricultural cultivation on climate change. The impact of three cultivation systems and four different crops on soil carbon sequestration was assessed in detail. To deepen the assessment, five soil carbon stock indicators (defined later in the text) were used.

RESEARCH LOCATION

The study was conducted in Poland, in the village of Sahryń, Werbkowice commune, Hrubieszów County, Lublin Voivodship, on chernozem soil, agrotechnical category IV (heavy soils), valuation class IIIa, and a good wheat production suitability complex (complex 2). All experimental plots were located in a single complex, on soils with homogeneous properties.

The weather conditions during the experiment are given in Table 1. The amount of precipitation during the vegetation period in the study years ranged from 448 mm in the 2021 season to 420 mm in 2023, i.e. they were comparable. During the experiment, precipitation and temperature did not differ from the averages of previous years.

Table 1. Weather conditions during the study period (own study based on data from state meteorological services)

Month	Monthly rainfall (mm)	Monthly temperature (average, °C)
2021		
Aug	77	13.8
Sep	18	9.3
Oct	3	5.6
Nov	42	0.5
Dec	32	−1.4
2022		
Jan	33	0.7
Feb	7	0.9
Mar	78	5.8
Apr	18	12.3
May	67	16.8
Jun	73	20.1
Jul	100	19.8
Aug	112	20.8
Sep	174	11.7
Oct	77	10.4
Nov	67	3.5
Dec	119	−0.7
2023		
Jan	116	2.0
Feb	47	0.5
Mar	104	4.6
Apr	75	8.2
May	41	13.5
Jun	140	17.2
Jul	112	20.3
Aug	59	20.9
Sep	33	17.5
Oct	106	11.1

Source: own elaboration.

STUDIED CROPS

The subject of the research were four crops commonly grown in Polish agriculture. The following crops were assessed:
- sugar beet,
- corn,
- winter wheat,
- winter rapeseed.

The cultivars of crop plants used in the experiment are presented in Table 2.

Table 2. Cultivars of crop plants used in the experiment

Species	Years/growing season	
	2022	**2023**
Sugar beet	'Jaromir' (KHBC)	'Viola KWS' (KWS)
Corn	'Libretto' (Saatbau, FAO 240)	'P8604' (Pioneer, FAO 220-230)
Winter wheat	'Moschus' (IGP)	'Moschus' (IGP)
Winter oilseed rape	'LG Antigua' (Limagrain)	'LG Antigua' (Limagrain)

Source: own elaboration.

CULTIVATION SYSTEMS

The experiment used two cultivation systems: conventional and conservation, in two variants: no-till and strip-till:
1) conventional cultivation (ploughing);
2) conservation agriculture systems:
   - no-till (NT),
   - strip-till (ST).

The differences between the experience variants will be the result of experience.

SOIL SAMPLING AND ANALYSIS

The soil sample was representative of the entire studied profile, with material collected once a year from a depth of 0–30 cm in mid-September. The granulometric composition was analysed in a single repetition, while all remaining parameters were determined in six replicates. Chemical analyses were carried out using the methods listed in Table 3. Results of granulometric composition for 2022 and 2023 are presented in Tables 4 and 5, respectively, and basic soil property data from the field experiments are shown in Table 6. The outcomes of chemical analyses and the calculated soil carbon stock indicators (Tabs. 7 and 8) were subjected to statistical processing using multifactor analysis of variance (ANOVA) in Statistica ver. 10, with Tukey's test applied to assess differences between mean values at a significance threshold of $p < 0.05$.

The carbon stock indices in cultivated soils were determined using the classical method developed by Blair, Lefroy and Lisle (1995), with modifications. The results were compared to a fallow reference sample. The following indices were calculated:
1) total organic carbon (TOC) – organic carbon resources per hectare were calculated to a depth of 0–30 cm;
2) carbon pool index (*CPI*): TOC (mg·kg^{-1}) in the tested soil / TOC (mg·kg^{-1}) in the reference soil; this index represents changes in total organic carbon relative to the reference soil;
3) organic carbon lability (*L*): labile fraction (L = C in the fraction oxidised by $KMnO_4$ / C remaining unoxidised by $KMnO_4$) unoxidised; it indicates the proportion of labile (easily decomposable) organic carbon in the soil;
4) lability index (*LI*): *L* in the tested soil / *L* in the reference soil; it measures how easily organic carbon is broken down compared to the reference soil.

Table 3. Soil analysis methods

Designated parameter	Test procedure / standards / test technique
Granulometric composition	Casagrande's areometric method, modified by Prószyński
pH	solutions in H_2O and KCl 1:5 (v/v) according to PN-ISO 10390:1
TOC	infrared detector (NDIR) analyser, based on the research procedure BL-PB-17
DOC	analysers with infrared detection (NDIR), aqueous extracts, filtered through a 0.45 μm filter
$CaCO_3$	Ostrowska *et al.* (1991)
Total N (Kjeldahl)	PN-EN 16169:2012
Hydrolytic acidity	Kappen's method
Carbon lability	method: Weil *et al.* (2003)

Explanations: TOC = total organic carbon, DOC = dissolved organic carbon.
Source: own elaboration.

5) carbon management index (*CMI*): *CPI* · *LI* · 10; this index assesses the effectiveness of different management practices in maintaining or improving soil carbon stocks.

The correlation matrix was calculated using the Pearson linear correlation coefficient.

RESULTS AND DISCUSSION

The granulomeric composition of the soil in the 2022 and 2023 experiments is presented in Table 4. The correlation matrix between soil particle-size fractions and organic matter indicators is shown in Table 5. A discussion of these studies is presented in the following sections of the article.

Soil acidity (Tab. 6) pH-H_2O and pH-KCl were relatively undifferentiated and characteristic for agricultural crops. No clear trends were observed depending on the cultivation method or plant type. The highest pH-H_2O values 7.99 were observed in no till (NT) sugar beet and 7.85 in conventional tillage (CT) winter wheat, while the lowest were 6.72 in NT corn and 6.84 in CT sugar beet. For pH-KCl, the highest value (7.40) was measured in CT winter wheat and the lowest (5.90) in NT corn.

Total nitrogen (N) is a key factor that influences soil productivity. Our study found no significant differences in soil N content between different crops (Tab. 6). However, in terms of tillage system, the total N content was higher in NT and ST systems than in CT systems. This difference ranged from 10 to 20%. Hydrolytic acidity showed greater variability from 0.75 to 1.80 cmol(+)·(kg soil)$^{-1}$ and was dependent on both crop type and tillage system, highlighting the complex interactions between soil, crop, and cultivation practices. No significant relationship was found between the types of crops and the crop species.

The effect of crop type and cultivation method on total organic carbon (TOC) content and labile organic carbon fraction (*L*) is shown in Table 7. The study confirmed that both crop type and cultivation method significantly influence TOC content. Content of TOC in soil varied depending on the crop, in the following order: sugar beet < corn < winter wheat < winter rapeseed. A similar trend was observed for *L* sugar beet < corn < winter wheat < winter rapeseed.

A statistical analysis of the results showed that the TOC content of the soil in all NT crop variants was statistically significantly higher than in CT: 12.9% for sugar beet, 15.6% for winter wheat and winter rapeseed, and 17.1% for corn. Values of TOC were also higher in ST cultivation than in CT cultivation, but these differences were statistically significant only for corn (9.0%) and winter rapeseed (11.2%). The carbon content in the *L* fraction in reduced crops (NT and ST) was consistently higher than in conventional cultivation. However, statistically significant differences were observed for NT crops: corn by 3%, winter wheat by 4%, and winter rapeseed by 5%. In the case of ST cultivation, only winter wheat showed a statistically significant difference of 4%. All the above data refer to averages from two years of research.

The values of soil quality indicators related to soil organic carbon – namely the carbon pool index (*CPI*), the carbon lability index (*LI*) and the carbon management index (*CMI*) – were statistically higher for all plant species in the NT system than in the CT system. The corresponding data are presented in Table 8. Only in the case of *CMI* in sugar beet cultivation was this difference statistically insignificant. In the case of ST, the variability of the indices was relatively large, with generally lower results than for the NT system but higher than for the CT system.

Comparison of our results (discussion) with studies by other authors largely confirms our conclusions. Our research has shown no significant differences in soil pH were observed between the different cropping systems. This finding is consistent with previous studies by Crozier *et al.* (1999), Rhoton (2000), and Thomas, Dalal and Standley (2007), which also reported no significant differences in pH between CTl and NT cropping systems. However, a global meta-analysis by Zhao *et al.* (2022) based on 1,059 observations from 114 publications found that soils under reduced tillage (no-till and strip-till) had a significantly lower pH than conventionally tilled soils; the difference was 1.33% (±0.28%). Additionally, Martínez *et al.* (2016) observed a slight decrease in soil pH under NT, but only within the top 10 cm of soil.

Our results indicating higher N content in NT and ST cultivation systems than CT confirmed the studies of other authors (Halvorson, Wienhold and Black, 2002; Puget and Lal, 2005; Omonode *et al.*, 2006; Spargo *et al.*, 2008; Varvel and Wilhelm, 2011). Other researchers (Gál *et al.*, 2007; Souza *et al.*, 2016) have also reported higher N levels in reduced tillage systems, mainly in the top 15–30 cm of soil. Cultivation under the NT system also protects soil nitrogen from leaching during heavy rainfall (Hess *et al.*, 2020; Zhang *et al.*, 2020).

The cultivation method significantly impacted TOC levels and other soil quality indicators. Soils that were conventionally tilled contained significantly less TOC and had lower values for other indicators compared to reduced tillage systems (NT and ST). These findings are consistent with previous studies demonstrating that reduced tillage promotes soil carbon accumulation and improves soil quality indicators (Ghosh *et al.*, 2016; Gong *et al.*, 2019; Mahala *et al.*, 2023). Begum *et al.* (2022) emphasised in particular that strip tillage improves the chemical and biological properties of the soil, increasing TOC and other soil quality indicators to a lesser extent than no-till.

Table 4. Granulometric composition of the soil

Crop plant	Tillage	Percentage share of fraction, size of fraction in mm													Textural class
		gravel >2	sand					silt			clay <0.002	Σ sand 2–0.05	Σ silt 0.05–002	clay <0.002	
			2–1	1–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.050–0.020	0.020–0.005	0.005-0.002					
Collection 2022															
Sugar beet	no-till	0	0	0	2	8	17	30	18	12	13	27	60	13	loamy silt
Corn		0	0	1	3	5	11	34	22	5	19	20	61	19	loamy silt
Winter wheat		0	0	0	2	6	14	39	22	6	10	23	67	10	loamy silt
Winter rapeseed		0	0	0	2	5	18	40	20	5	9	26	65	9	clayey silt
Sugar beet	conventional	0	0	0	1	4	22	34	18	8	12	28	60	12	loamy silt
Corn		0	0	0	1	4	15	37	20	8	14	21	65	14	loamy silt
Winter wheat		0	1	2	3	11	18	41	16	5	3	35	62	3	loamy silt
Winter rapeseed		0	0	0	1	3	14	36	16	10	19	19	62	19	sandy loam
Sugar beet	strip till	0	0	1	6	14	12	34	17	9	7	33	60	7	loamy silt
Corn		0	0	1	6	12	10	34	20	6	10	30	60	10	loamy silt
Winter wheat		0	0	0	0	1	14	44	22	4	15	15	70	15	clayey silt
Winter rapeseed		0	0	0	0	1	14	47	18	6	13	16	71	13	loamy silt
Collection 2023															
Sugar beet	no-till	0	0	1	3	4	11	38	21	9	12	20	68	12	silty loam
Corn		0	0	1	2	4	11	41	24	6	11	18	71	11	silty loam
Winter wheat		0	1	1	3	7	17	32	16	13	11	28	61	11	silty loam
Winter rapeseed		0	0	2	7	6	14	32	19	6	14	29	57	14	silty loam
Sugar beet	conventional	0	0	0	1	3	14	41	20	8	12	19	69	12	silty loam
Corn		0	1	1	2	4	10	41	22	10	9	18	73	9	silty loam
Winter wheat		0	0	1	2	6	24	34	18	3	11	34	55	11	silty loam
Winter rapeseed		0	1	4	4	11	28	25	18	3	6	48	46	6	loamy sand
Sugar beet	strip till	0	1	1	2	4	13	40	19	10	10	21	69	10	silty loam
Corn		0	0	2	6	6	23	29	15	9	10	37	53	10	silty loam
Winter wheat		0	0	1	1	1	14	47	19	4	14	16	70	14	silty loam
Winter rapeseed		0	1	1	1	1	14	48	20	7	7	18	75	7	silty loam

Source: own study.

Table 5 Correlation matrix between soil particle-size fractions and organic matter indicators

Parameter	>2	2–1	1–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.005	0.005–0.002	<0.002	Σsand (2–0.5)	Σsilt (0.05–0.002)	Clay <0.002	TOC_avg	*CPI*_avg	Labile_avg	Labilty_index_avg	*CMI*-avg
>2																		
2–1		**1.00**	0.75	0.12	0.36	0.29	0.23	−0.43	−0.26	−0.61	0.51	−0.13	0.61	0.06	0.06	−0.19	−0.20	0.02
1–0.5		0.75	**1.00**	0.66	0.71	−0.23	−0.10	−0.27	−0.28	−0.53	0.65	−0.44	−0.53	−0.18	−0.18	−0.16	−0.15	−0.19
0.5–0.25		0.12	0.66	**1.00**	0.92	−0.47	−0.51	−0.11	0.06	−0.46	0.73	−0.65	−0.46	−0.36	−0.36	−0.08	−0.07	−0.34
0.25–0.1		0.36	0.71	0.92	**1.00**	−0.22	−0.50	−0.31	0.19	−0.67	0.89	−0.67	−0.67	−0.43	−0.42	−0.20	−0.19	−0.41
0.1–0.05		0.29	−0.23	−0.47	−0.22	**1.00**	0.02	−0.34	0.16	−0.27	0.23	−0.06	−0.27	−0.13	−0.12	−0.28	−0.29	−0.14
0.05–0.02		0.23	−0.10	−0.51	−0.50	0.02	**1.00**	0.12	−0.66	−0.13	−0.46	0.89	−0.13	0.72	0.72	0.49	0.47	0.71
0.02–0.005		−0.43	−0.27	−0.11	−0.31	−0.34	0.12	**1.00**	−0.54	0.31	−0.46	0.38	0.31	0.32	0.32	0.70	0.69	0.38
0.005–0.002		−0.26	−0.28	0.06	0.19	0.16	−0.66	−0.54	**1.00**	0.18	0.18	−0.50	0.18	−0.57	−0.57	−0.62	−0.60	−0.60
<0.002		−0.61	−0.53	−0.46	−0.67	−0.27	−0.13	0.31	0.18	**1.00**	−0.79	0.12	1.00	0.03	0.02	−0.07	−0.06	0.01
Σsand (2–0.5)		0.51	0.65	0.73	0.89	0.23	−0.46	−0.46	0.18	−0.79	**1.00**	−0.70	−0.79	−0.46	−0.45	−0.33	−0.32	−0.45
Σsilt (0.05–0.002)		−0.13	−0.44	−0.65	−0.67	−0.06	0.89	0.38	−0.50	0.12	−0.70	**1.00**	0.12	0.71	0.71	0.62	0.60	0.72
Clay <0.002		−0.61	−0.53	−0.46	−0.67	−0.27	−0.13	0.31	0.18	1.00	−0.79	0.12	**1.00**	0.03	0.02	−0.07	−0.06	0.01
TOC_avg		0.06	−0.18	−0.36	−0.43	−0.13	0.72	0.32	−0.57	0.03	−0.46	0.71	0.03	**1.00**	1.00	0.74	0.71	1.00
*CPI*_avg		0.06	−0.18	−0.36	−0.42	−0.12	0.72	0.32	−0.57	0.02	−0.45	0.71	0.02	1.00	**1.00**	0.75	0.71	1.00
Labile_avg		−0.19	−0.16	−0.08	−0.20	−0.28	0.49	0.70	−0.62	−0.07	−0.33	0.62	−0.07	0.74	0.75	**1.00**	0.99	0.80
Labilty_index_avg		−0.20	−0.15	−0.07	−0.19	−0.29	0.47	0.69	−0.60	−0.06	−0.32	0.60	−0.06	0.71	0.71	0.99	**1.00**	0.76
CMI-avg		0.02	−0.19	−0.34	−0.41	−0.14	0.71	0.38	−0.60	0.01	−0.45	0.72	0.01	1.00	1.00	0.80	0.76	**1.00**

Explanations: TOC = total organic content, *CPI* = carbon pool index, *CMI* = carbon management index.
Source: own study.

Table 6. The influence of the tillage method on the properties and chemical composition of the soil

Crop plant	Method of tillage	pH-H_2O			pH-KCl			N total (%)			Hydrolitic acidity (cmol(+)·(kg soil)$^{-1}$)		
		2022	2023	average	2022	2023	average	2022	2023	average	2022	2023	average
Sugar beet	conventional	5.76	7.92	6.84	5.16	7.65	6.41	0.21	0.22	0.21	1.37	0.71	1.04
	no-till	8.25	7.72	7.99	7.63	7.04	7.34	0.25	0.24	0.25	0.76	0.74	0.75
	strip till	7.31	7.80	7.56	6.62	7.34	6.98	0.21	0.27	0.24	0.85	0.80	0.82
Corn	conventional	7.86	7.79	7.83	7.42	7.37	7.40	0.18	0.20	0.19	0.86	0.66	0.76
	no-till	6.50	6.93	6.72	5.23	6.57	5.90	0.22	0.20	0.21	1.84	1.76	1.80
	strip till	7.62	6.46	7.04	7.19	5.39	6.29	0.18	0.23	0.21	0.93	1.21	1.07
Winter wheat	conventional	7.99	7.71	7.85	7.54	7.26	7.40	0.21	0.21	0.21	1.05	0.95	1.00
	no-till	7.37	7.61	7.49	6.51	7.51	7.01	0.25	0.25	0.25	1.22	0.83	1.02
	strip till	7.80	7.57	7.69	7.26	7.40	7.33	0.20	0.25	0.23	1.15	0.72	0.94
Winter rapeseed	conventional	8.06	6.76	7.41	7.49	5.59	6.54	0.19	0.18	0.18	0.90	1.39	1.14
	no-till	7.94	7.43	7.69	7.52	7.08	7.30	0.20	0.23	0.21	0.97	1.32	1.15
	strip till	7.37	7.59	7.48	7.03	7.36	7.20	0.18	0.22	0.20	1.20	0.97	1.08

Source: own study.

Table 7. Soil carbon stock indices

Crop plant	Method of tillage	Total organic carbon content			Labile organic carbon fraction content		
		2022	2023	average	2022	2023	average
		mg·kg^{-1}					
Sugar beet	conventional	15,300 ±168	15,000 ±201	15,150a	655 ±72	717 ±69	686a
	no-till	17,500 ±203	16,700 ±187	17,100b	695 ±80	708 ±81	702a
	strip till	16,100 ±141	15,800 ±130	15,950a	661 ±92	740 ±29	700a
Corn	conventional	15,400 ±167	17,900 ±167	16,650a	690 ±67	699 ±76	694a
	no-till	19,300 ±232	19,900 ±206	19,600b	712 ±92	715 ±90	713b
	strip till	17,300 ±201	19,000 ±248	18,150b	696 ±74	714 ±86	705a
Winter wheat	conventional	20,300 ±197	19,900 ±250	20,100a	687 ±96	707 ±90	697a
	no-till	21,700 ±209	24,800 ±309	23,250b	755 ±89	694 ±70	725b
	strip till	20,500 ±342	22,700 ±284	21,600a	713 ±98	728 ±93	721b
Winter rapeseed	conventional	20,300 ±247	20,800 ±274	20,550a	695 ±89	674 ±89	685a
	no-till	23,800 ±251	23,700 ±273	23,750b	680 ±93	770 ±62	725b
	strip till	23,500 ±321	22,200 ±264	22,850b	683 ±78	750 ±91	716a

Explanations: the data presented for each year are the average result of four repetitions with standard deviation (*SD*). Lowercase letters (a, b) mean significant differences between conventional tillage and the other treatments for the plants tested at $p = 0.05$.
Source: own study.

There is great diversity, and even contradiction, in the scientific literature regarding the impact of simplified cultivation methods on soil carbon content. These differences are caused by many factors influencing the processes that shape the level and properties of C in the soil, apart from the cultivation method and crop species (Bhattacharyya *et al.*, 2022; Dash *et al.*, 2025). The literature mainly shows that the highest concentration of C in NT technologies is located in the top 10 cm of soil, whereas in layers deeper than 30 cm, the cultivation method has no influence and conventional technologies have an advantage over C sequestration. In our studies, TOC levels in the NT technology were statistically higher than in the CT in the 0–30 cm layer, i.e. the ploughing depth.

Soil quality indicators (*SQI*, *CMI*, *LI*) are crucial for assessing the impact of land use on soil degradation and carbon loss (Zhang *et al.*, 2023). The carbon management index (*CMI*)

Table 8. Three key soil quality indicators

Crop plant	Method of tillage	Carbon pool index			Lability index			Carbon management index		
		2022	2023	average	2022	2023	average	2022	2023	average
Sugar beet	conventional	1.28 ±0.26	1.25 ±0.31	1.26a	1.06 ±0.28	1.16 ±0.26	1.11a	135 ±14	145 ±26	140a
	no-till	1.46 ±0.38	1.39 ±0.43	1.43b	1.13 ±0.31	1.15 ±0.32	1.14a	164 ±17	160 ±19	162b
	strip till	1.34 ±0.42	1.32 ±0.39	1.33a	1.07 ±0.30	1.20 ±0.29	1.14a	144 ±16	158 ±20	151b
Corn	conventional	1.28 ±0.30	1.49 ±0.42	1.39a	1.12 ±0.32	1.13 ±0.23	1.13a	144 ±16	169 ±19	156a
	no-till	1.61 ±0.45	1.66 ±0.53	1.63b	1.15 ±0.36	1.16 ±0.27	1.16b	186 ±23	192 ±21	189b
	strip till	1.44 ±0.46	1.58 ±0.36	1.51b	1.13 ±0.39	1.16 ±0.31	1.14b	163 ±17	183 ±29	173b
Winter wheat	conventional	1.69 ±0.50	1.66 ±0.59	1.68a	1.11 ±0.29	1.15 ±0.23	1.13a	188 ±14	190 ±21	189a
	no-till	1.81 ±0.56	2.07 ±0.61	1.94b	1.22 ±0.24	1.13 ±0.26	1.17b	221 ±32	233 ±34	227b
	strip till	1.71 ±0.43	1.89 ±0.58	1.80a	1.16 ±0.22	1.18 ±0.23	1.17b	198 ±20	223 ±24	210a
Winter rape-seed	conventional	1.69 ±0.54	1.73 ±0.46	1.71a	1.13 ±0.26	1.09 ±0.26	1.11a	191 ±19	189 ±21	190a
	no-till	1.98 ±0.51	1.98 ±0.61	1.98b	1.10 ±0.28	1.25 ±0.31	1.18b	219 ±32	247 ±39	233b
	strip till	1.96 ±0.71	1.85 ±0.62	1.90b	1.11 ±0.26	1.21 ±0.27	1.16b	217 ±27	225 ±37	221b

Explanations: the data presented for each year are the average result of four repetitions with standard deviation (*SD*). Lowercase letters (a, b) significant differences between conventional tillage and the other treatments for the plants tested at p = 0.05.
Source: own study.

determines changes in organic carbon content compared to the reference value (Parihar *et al.*, 2018). In CA systems, the higher content of macroaggregates compared to CT limits mineralisation, thereby protecting organic C and resulting in a higher *CMI* value and improved soil structure (Lal, 2008). A low *CMI* value suggests ongoing soil degradation characterised by lower carbon input and faster carbon losses (Zhang *et al.*, 2023). Our research indicates that soils in simplified tillage systems were characterised by higher *CMI* values, especially in the NT system.

The *LI* is a sensitive indicator of carbon transformation in soil, representing the fraction that can be oxidised by 333 mM $KMnO_4$ (Blair, Lefroy and Lisle, 1995). Higher *LI* values promote the stabilisation of organic C and soil aggregates, as well as having a beneficial effect on microbiological activity (Vieira *et al.*, 2007; Balontayová *et al.*, 2025). An increase in TOC content had no significant effect on *LI* content. A negative correlation was found between *LI* and catalase activity, and a positive correlation with total nitrogen (Kondratowicz-Maciejewska, Lemanowicz and Jaskulska, 2025). Research by Begum *et al.* (2022) showed no difference in *LI* index value between CT and NT cultivation methods. The results of our study confirm the beneficial effect of reduced tillage, especially NT, on the *LI* value.

The *CMI* is widely recognised as an effective, sensitive tool for quantifying changes in soil quality (Blair, Lefroy and Lisle, 1995; Ghosh *et al.*, 2016). Several researchers (Six, Elliott and Paustian, 2000; Moharana *et al.*, 2012; Mandal *et al.*, 2022) have recommended the *CMI* as an early-warning indicator of soil degradation, emphasising its importance in agricultural land management strategies. An increase in *CMI* values indicates correct cultivation technology and its impact on soil quality (Vieira *et al.*, 2007; Nthebere *et al.*, 2025). Our studies have shown a beneficial effect of NT on the *CMI* index.

CONCLUSIONS

The use of conservation tillage (CT) systems: no-till (NT) and strip tillage (ST) increase the N content in the soil compared to conventional tillage. There was no effect of conventional and conservation cultivation methods or plant type on soil pH. The total organic (TOC) content increased depending on the crop: sugar beet < corn < winter wheat < winter rapeseed. Similarly to labile organic carbon fraction (*L*): sugar beet < corn < winter wheat < winter rapeseed.

Statistical analysis showed that the TOC content in the NT system was significantly higher than in the CT in all experimental variants (cultivation method, type of crop). The values of soil quality indices Carbon pool index (*CPI*), Lability index (*LI*) and carbon management index (*CMI)* for all plant species were statistically higher in the NT system than in the CT system (except for *CMI* for sugar beet, the differences were insignificant).

The use of the ST method has a positive effect on the TOC content and soil quality indicators compared to CT, but to a lesser extent than NT.

In general, conservation farming methods contribute significantly to mitigating climate change compared to conventional methods.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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