

Crop Productivity and Soil Benefits through Carbon Sequestration - Importance for Farm Management

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Abstract. The productivity of agricultural crops through carbon sequestration was analyzed in this study. The research was located at Agricultural Research and development Station (ARDS) Lovrin, Romania. Wheat (W), maize (M), and industrial hemp (IH) were cultivated under four soil tillage variants: disc (StD), shallow scarification (StSS), deep scarification (StDS), and ploughing (StP). Based on results, the industrial hemp crop sequestered the largest amount of carbon in biomass (601.00 t ha⁻¹) and in soil (163.75 t ha⁻¹), followed by the corn crop (242.25 t ha⁻¹ in biomass; 66.00 t ha⁻¹ in soil), and the winter wheat crop (227.25 t ha⁻¹ in biomass; 61.75 t ha⁻¹ in soil). In relation to soil tillage, tillage by ploughing (StP) favoured carbon sequestration in hemp (620 t ha⁻¹ in biomass; 169 t ha⁻¹ in soil), and corn (253 t ha⁻¹ in biomass; 69 t ha⁻¹ in soil). In winter wheat, tillage by disc harrow (StD) favoured a higher amount of carbon sequestration (244 t ha⁻¹ in biomass; 66 t ha⁻¹ in soil). The results of the study are important for management decisions at the farm level, in the context of climate change.

Keywords: carbon sequestration, comparative analysis, crop productivity, farm management, soil tillage systems

INTRODUCTION

The sustainability of farms and farmers relies on crop productivity, which is increasingly difficult in the context of changing economic and climatic conditions (Pretty, 2008; Ejeta and Bai, 2025; Miriti and Lambarra-Lehnhardt, 2025).

In the context of climate change, economic aspects and trends of agricultural crops and products were evaluated at different levels - local, regional, global, and potential solutions for farm sustainability, food safety and security were considered (Chetroui and Ilie, 2024; Ionitescu et al., 2024; Kaplan et al., 2024; Saracin et al., 2024; Popescu et al., 2025).

Reducing carbon emissions, correlated with carbon sequestration, in the context of climate change, represent priority directions at a global level for mitigating climate effects (Murphy, 2025; Tölgyesi et al., 2025; Dahiya et al., 2026).

Higher plants and algae capture and fix carbon through the process of photosynthesis, correlated with biological specificity and influencing factors (Matthews, 2023; Muller-Feuga, 2024; Rudenko, 2025).

Plants of agricultural interest have variable yields for total biomass, for useful production, usable for human food, animal feed, raw material for different economic sectors (Roberts and Mattoo, 2019; Rodino, 2024; Ali et al., 2025).

By engineering photosynthesis, agricultural crops capture large amounts of carbon, and present an important lever for carbon sequestration (Arellano Vazquez et al., 2024; Frank et al., 2024; Villat and Nicholas, 2024).

Carbon agriculture integrates a series of packages and complexes of agricultural practices, promoted among farmers for ecosystem services and climate change mitigation, and which would need to be supported by certain rewards for their implementation and promotion (Debernardini et al., 2025; Yadav et al., 2025). The potential for carbon agriculture, ecosystem services and effects in relation to climate change, was analyzed in relation to different influencing factors (Strauss et al., 2024; Yadav et al., 2025).

The amount of carbon sequestered varies in relation to crop plants (e.g. wheat, sunflower, corn, energy crops), agricultural systems (e.g. intensive, biological, biodynamic), soil tillage systems (e.g. plowing, no-till, minimal-till), technological practices (e.g. irrigation, organic and mineral fertilization), vegetation conditions (Purwanto and Alam, 2020; Zhang et al., 2024; Deis et al., 2025; Moore et al., 2025).

Sustainable intensification of agricultural systems is of interest and importance both from the perspectives of food safety and security, and carbon sequestration (Haughey et al., 2023).

Some studies have reported agricultural limitations in carbon sequestration, in relation to different specific influencing factors (Mattila and Vihanto, 2024).

Models for estimating yields and soil organic carbon, and soil carbon sequestration potential, in relation to different agricultural systems and climatic conditions, were communicated (Aragon et al., 2024; Giannitsopoulos et al., 2025; Metrikaitytė Gudelė and Sužiedelytė Visockienė, 2025).

Recent studies have reported options for improving soil carbon sequestration by adapting soil tillage, crop structure, and crop rotation (Ghimirey et al., 2025; Liu et al., 2026).

This study evaluated the amount of carbon sequestered by three agricultural crops, wheat, corn, industrial hemp, non-irrigated crop system, in relation to four soil work variants, under the specific conditions of ARDS Lovrin, Western Plain of Romania.

MATERIAL AND METHODS

The study was conducted under the specific conditions of ARDS Lovrin, within the ADER 19.1.1 project. Field research was conducted in the agricultural year 2024 – 2025, under non-irrigated conditions, chernozem soil conditions. The climatic conditions, in terms of temperature and precipitation, recorded in the experimental area, according to the records from ARDS Lovrin, are presented in Figure 1

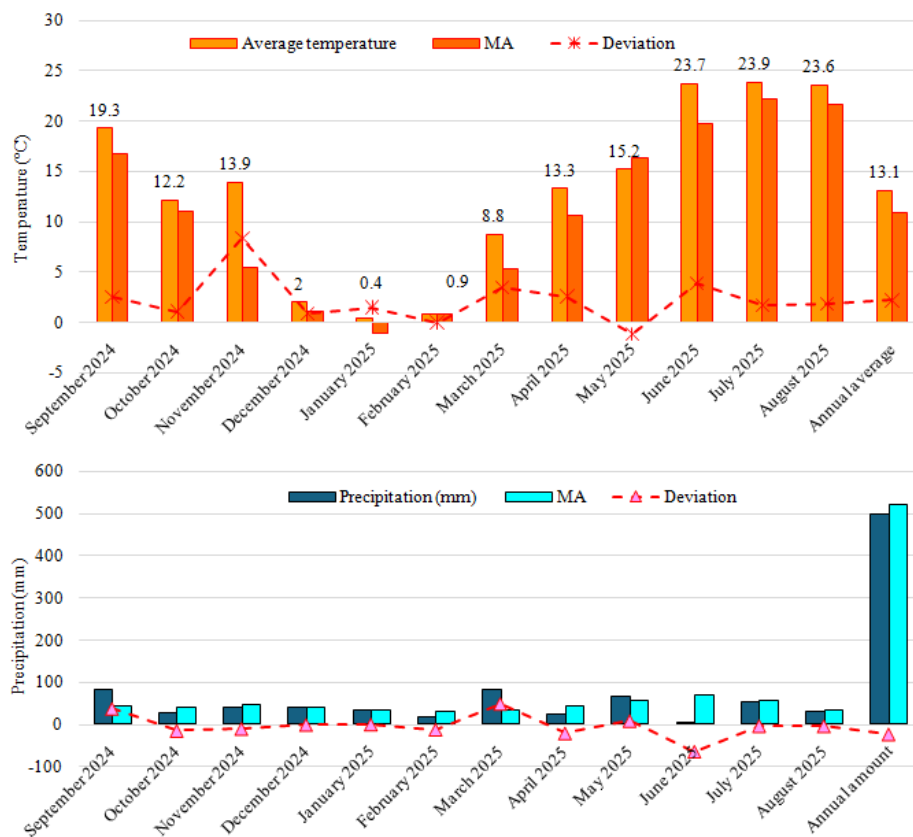


Figure 1. Climatic conditions during the experimental period, 2024 - 2025

Three crops were considered, wheat (W), corn (M) and industrial hemp (IH). For each crop, four types of tillage were performed: disc tillage (StD), shallow scarification (StSS), deep scarification (StDS) and ploughing (StP). Twelve experimental designs (T1 to T12) were produced, arranged in replicates.

To evaluate the carbon content sequestered by the three crops, in relation to the four soil tillage options, soil samples were taken from the 0 - 30 cm horizon, before sowing, and at the end of the vegetation period, after harvesting the crops. The determination of soil carbon was done under laboratory conditions with the NCHOS Elemental Analyzer, using the method developed by the manufacturing company VELP SCIENTIFICA. The transformation of organic carbon sequestered in soil into carbon dioxide captured by plants was based on the conversion of carbon (C) to carbon dioxide (CO₂), according to Equation (1) (Ramirez et al., 2025).

$$\text{CO}_2 = \text{C} \times \left(\frac{44}{12} \right) = \text{C} \times 3.67 \quad (1)$$

The study was conducted according to the flow shown in Figure 2.

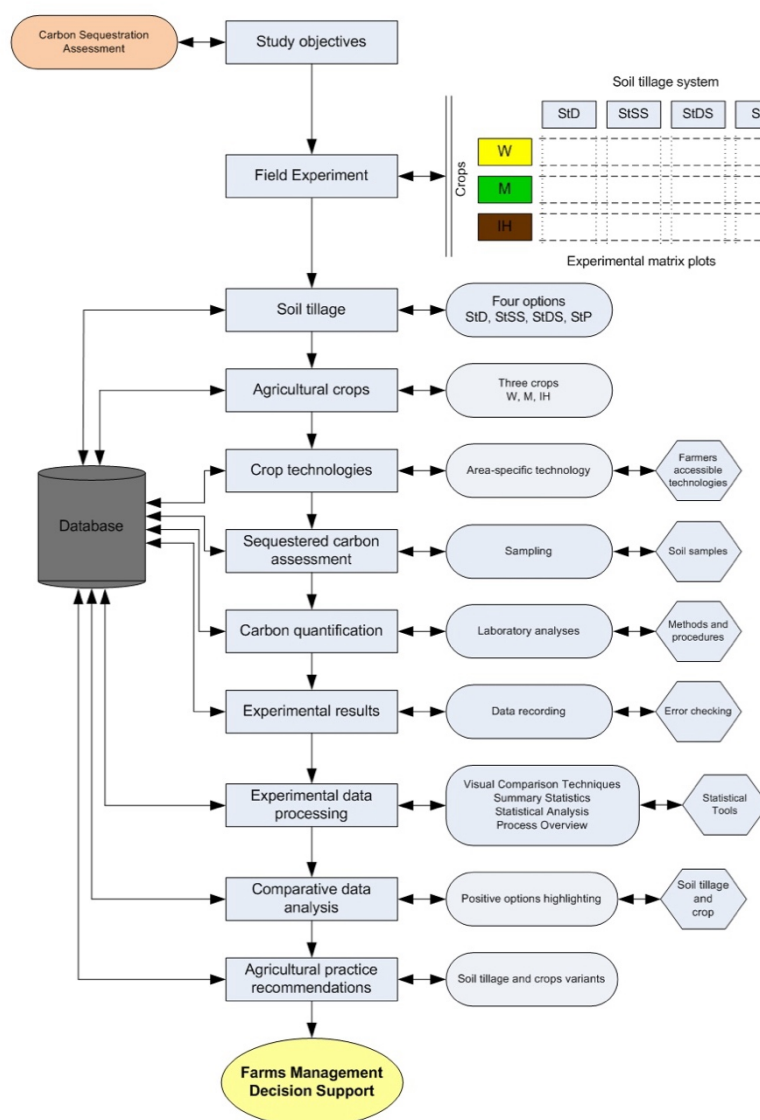


Figure 2. Logical scheme of the study

The experimental data were analyzed for an overall assessment of statistical reliability, the presence of variance, the identification of outlier values and the trend of data distribution. Comparative analysis was made between the experimental variants regarding the amount of carbon sequestered. Multivariate analysis was used to identify the correlation of variants, crop data and soil tillage system, based on the amount of carbon sequestered. Appropriate mathematical and statistical analysis tests were applied, and for this purpose the PAST software (Hammer et al., 2001) and the calculation module in EXCEL were used.

RESULTS AND DISCUSSIONS

The amount of carbon sequestered in the biomass of wheat, corn and sunflower crops and in the soil, under four soil tillage variants, was determined under experimental conditions within the ARDS Lovrin, agricultural year 2024 - 2025. The amount of carbon sequestered in crop biomass varied between $217 \pm 52,176 \text{ t ha}^{-1}$ (T3, W+StDS) and $620 \pm 52,176 \text{ t ha}^{-1}$ (T12, IH+StP, Table 1. The amount of carbon sequestered in soil varied between $59 \pm 14,228 \text{ t ha}^{-1}$ (T3, W+StDS) and $169 \pm 14,228 \text{ t ha}^{-1}$ (T12, IH+StP), Table 1. Within each crop, variations in the amount of carbon sequestered were recorded in relation to the soil tillage system. The ANOVA test confirmed the reliability of the experimental results and the presence of variance in the data set, Table 2.

The presence of outlier values in the experimental data series was evaluated. Outlier tests (Grubbstest, and Dixon Q test) showed that no significant outlier values were recorded in the data set for soil ($G = 1.457$, $p = 1$; $Q(r21) = 0.0642$, $p = 0.9943$) and crops ($G = 1.456$, $p = 1$; $Q(r21) = 0.0627$, $p = 0.9942$).

Table 1. Sequestered carbon content in the experimental variants

Crop	Soil tillage system	Trial	Carbon sequestration (t ha ⁻¹)	
			Biomass	Soil
Wheat (W)	StD	T1	244	66
	StSS	T2	221	60
	StDS	T3	217	59
	StP	T4	227	62
Mayze (M)	StD	T5	235	64
	StSS	T6	242	66
	StDS	T7	239	65
	StP	T8	253	69
Industrial Hemp (IH)	StD	T9	587	160
	StSS	T10	595	162
	StDS	T11	602	164
	StP	T12	620	169

Table 2. ANOVA Test results

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	404560.7	1	404560.7	23.0534	<0.001	4.3009
Within Groups	386075.3	22	17548.88			
Total	790636	23				

The trend of the data distribution, regarding the carbon sequestered content under the experimental conditions, was evaluated by statistical analysis. Mann-Kendall trend Test confirmed the statistically significant increasing trend of the data distribution both for soil samples ($S = 51$, $Z = 3.4367$, $p < 0.001$) and for crop samples ($S = 50$, $Z = 3.3601$, $p < 0.001$).

Comparative analysis of the data was made, in relation to soil works, in relation to crops, as well as a result of the interaction between the two factors. In relation to soil tillage, small differences were recorded for each crop regarding the amount of carbon sequestered in biomass, and the differences did not present statistical significance ($p > 0.05$) under the study conditions. Similar results were recorded for the content of carbon sequestered in soil, in relation to soil tillage. Clear differences were observed between crops regarding the amount of carbon sequestered, namely a much higher amount of industrial hemp compared to the other two crops, respectively wheat and corn, Figure 3.

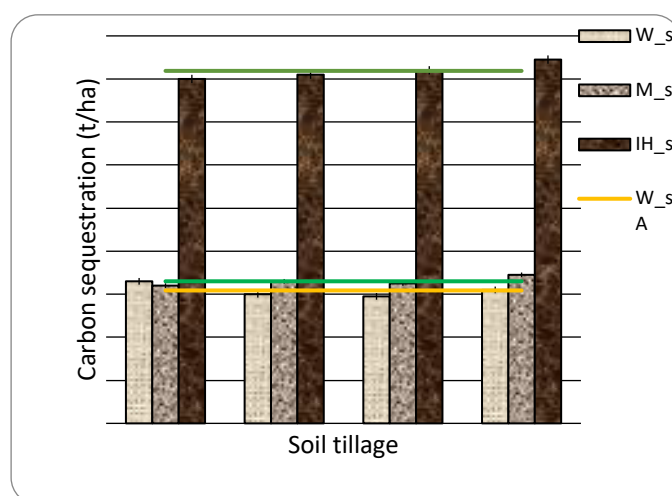


Figure 3. Amount of carbon sequestered in soil under study conditions; W – wheat, M – maize, IH – industrial hemp, s – soil, A – average value on soil tillage system

Comparative analysis was performed between crops, regarding the amount of carbon sequestered in biomass and soil, and obvious differences were recorded between the mean and median values. ANOVA Test confirmed statistically significant differences between the mean values of the amount of carbon sequestered in biomass and soil, Table 3.

Kruskal-Wallis test (for equal medians) confirmed significant differences between median values, regarding the amount of carbon captured, in biomass and soil, in relation to agricultural crops, with values $H(\chi^2) = 21.67$, H_c (tie corrected) = 21.68, $p < 0.001$.

Table 3. ANOVA Test results, mean values analysis

Statistical parameters	Values of Statistical parameters				
	Sum of sqrs	df	Mean square	F	p (same)
Between groups	789351	5	157870	2211	1.95E-24
Within groups	1285	18	71.389	Permutation p (n=99999)	
Total	790636	23	1.00E-05		
Components of variance (only for random effects)					
Var(group)	39449.7	Var (error)	71.389	ICC	0.998
omega ²	0.998				
Levene's test for homogeneity of variance, from means	p (same)	0.118			
Levene's test, from medians	p (same)	0.198			
Welch F test in the case of unequal variances	F=1436, df=8.03, p=1.274E-11				
Bayes factor	9.632E20 (decisive evidence for unequal means)				

Under these conditions, Dunn's Post Hoc test highlighted the statistical reliability in the comparative analysis of the variants (given by agricultural crops), regarding the amount of carbon sequestered in biomass and soil, Table 4, with the normal distribution of residual values, Figure 4.

Table 4. Dunn's Post Hoc test results

	W_b	M_b	IH_b	W_s	M_s	IH_s
W_b		0.6170	0.1470	0.0153	0.0607	0.3420
M_b	0.6170		0.3420	0.0034	0.0175	0.1470
IH_b	0.1470	0.3420		0.0001	0.0009	0.0164
W_s	0.0153	0.0034	0.0001		0.5822	0.1401
M_s	0.0607	0.0175	0.0009	0.5822		0.3549
IH_s	0.3420	0.1470	0.0164	0.1401	0.3549	

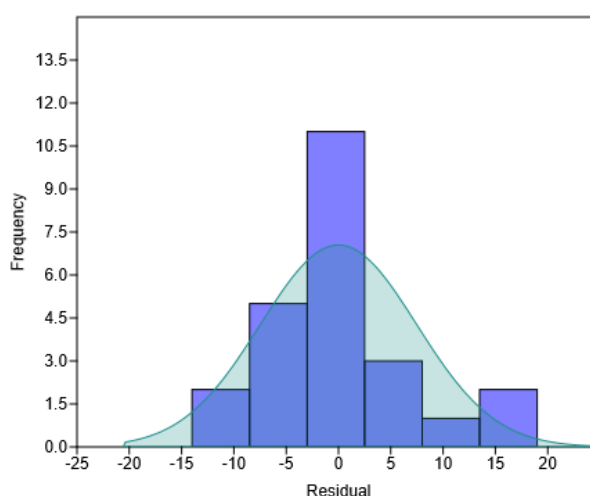


Figure 4. Normal distribution of residual values

In the case of carbon fixed in crop biomass, the average value at the experiment level was $\overline{SC}_b = 356.83 \text{ t ha}^{-1}$ (SC – sequestered carbon), Table 5.

In relation to the average value, wheat crops (T1 to T4) and corn (T5 to T8) presented lower values in the experimental variants. In the case of wheat crop, statistically significant negative differences were recorded in the variants T2, T3 and T4 ($p < 0.05$). In the case of corn crop, statistically significant negative differences were recorded in the variants T5 and T7 ($p < 0.05$). In the case of industrial hemp cultivation, positive differences were recorded, with statistical certainty at the $p < 0.01$ level (T9) and at the $p < 0.001$ level (T10, T11 and T12).

Table 5. Carbon sequestered differences in crop biomass by experimental variants, in relation to the average value of the experiment

Trials	Given mean	Sample mean	95% conf. interval	Difference	95% conf. interval	t	p (same mean)	Sig
T1	244	356.83	(241.99 471.67)	112.83	(-2.0056 227.67)	2.1625	0.0535	ns
T2	221			135.83	(20.994 250.67)	2.6034	0.0245	o
T3	217			139.83	(24.994 254.67)	2.6800	0.0214	o
T4	227			129.83	(14.994 244.67)	2.4884	0.0301	o
T5	235			121.83	(6.9944 236.67)	2.3350	0.0395	o
T6	242			114.83	(-0.0055647 229.67)	2.2009	0.0500	ns
T7	239			117.83	(2.9944 232.67)	2.2584	0.0452	o
T8	253			103.83	(-11.006 218.67)	1.9900	0.0720	ns
T9	587			230.17	(115.33 345.01)	-4.4113	0.0010	**
T10	595			238.17	(123.33 353.01)	-4.5647	0.0008	***
T11	602			245.17	(130.33 360.01)	-4.6988	0.0007	***
T12	620			263.17	(148.33 378.01)	-5.0438	0.0004	***

Note: o - symbol for negative differences, * symbol for positive differences; o – $p < 0.05$; ** – $p < 0.01$; *** $p < 0.001$

In the case of carbon fixed in the soil, the average value at the experiment level was $\overline{SC}_s = 97,167 \text{ t ha}^{-1}$, (SC – sequestered carbon), Table 6. The differences recorded between the experimental variants and the calculated average value presented similar statistical significance as in the case of carbon in the biomass of the tested crops. The graphic representation of the differences in the carbon content sequestered in biomass and soil, compared to the calculated average values, is given in figure 5.

Table 6. Carbon sequestered differences in soil by experimental variants, in relation to the average value of the experiment

Trials	Given mean	Sample mean	95% conf. interval	Difference	95% conf. interval	t	p (same mean)	Sig
T1	66	97.167	(65.85 128.48)	31.167	(-0.15012 62.483)	2.1904	0.0509	ns
T2	60			37.167	(5.8499 68.483)	2.6121	0.0242	o
T3	59			38.167	(6.8499 69.483)	2.6824	0.0213	o
T4	62			35.167	(3.8499 66.483)	2.4716	0.0310	o
T5	64			33.167	(1.8499 64.483)	2.331	0.0398	o
T6	66			31.167	(-0.15012 62.483)	2.1904	0.0509	ns
T7	65			32.167	(0.84988 63.483)	2.2607	0.0450	o
T8	69			28.167	(-3.1501 59.483)	1.9796	0.0733	ns
T9	160			62.833	(31.517 94.15)	-4.416	0.0010	**
T10	162			64.833	(33.517 96.15)	-4.5566	0.0008	***
T11	164			66.833	(35.517 98.15)	-4.6971	0.0007	***
T12	169			71.833	(40.517 103.15)	-5.0485	0.0004	***

Note: o - symbol for negative differences, * symbol for positive differences; o – $p < 0.05$; ** – $p < 0.01$; *** $p < 0.001$

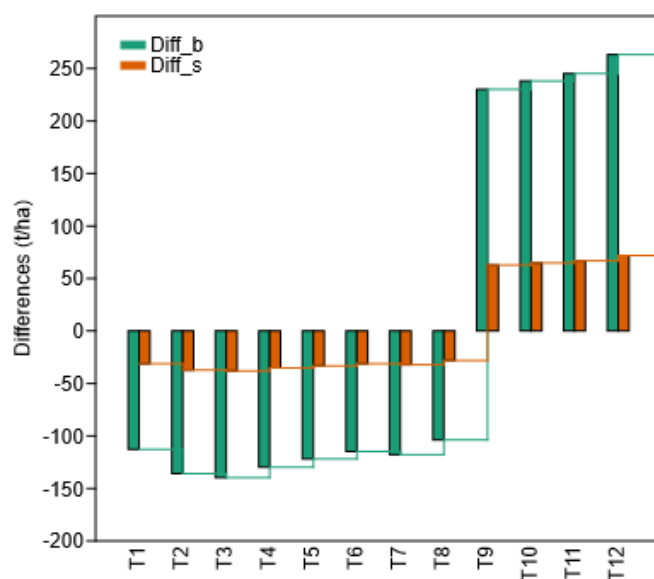


Figure 5. Graphical distribution of differences for sequestered carbon by experimental variants

Multivariate analysis showed the correlation of crops with soil tillage, in relation to the amount of carbon sequestered, under the study conditions, Figure 6. The main two components explained 97.716% of the total variance. The correlation of wheat crop with disk tillage (StD) was observed, respectively the correlation of corn and industrial hemp crops with plow tillage (StP), both for carbon fixed in biomass and for carbon fixed in soil.

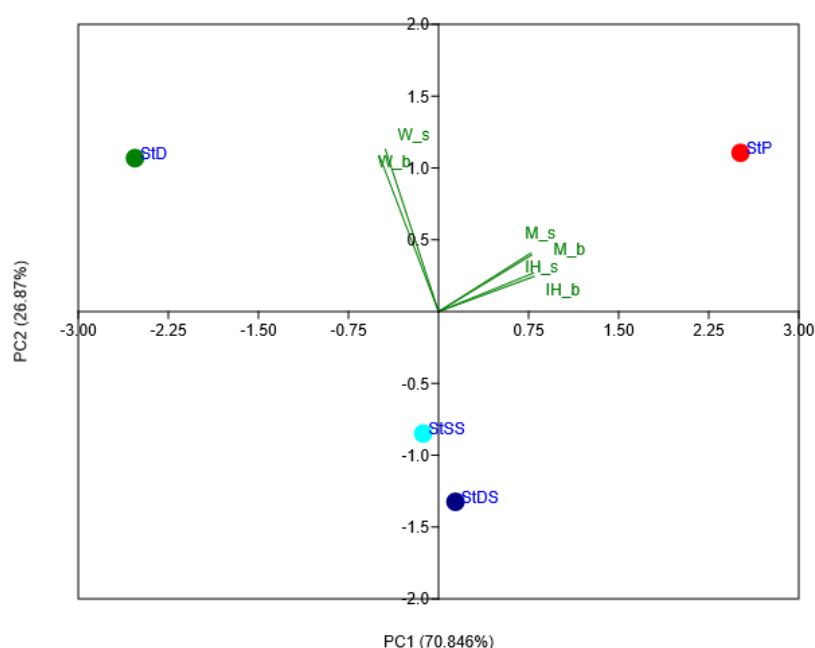


Figure 6. PCA diagram regarding the correlation of crops with soil works based on the amount of carbon sequestered

According to the PCA analysis, the tillage variant with the plow (StP) presented the highest score in relation to the principal components (StP = 2.5148), Table 7. This tillage variant, in relation to the industrial hemp crop (IH), T12 experimental trial, led to the highest value of carbon sequestered under the study conditions, Table 1. In the corn crop (M), the StP tillage variant also generated the highest amount of carbon sequestered in the soil, Table 1.

Among the crops, industrial hemp (IH) presented the highest loading value in relation to the principal components, both for biomass (IH_b = 0.4686) and for soil (IH_s = 0.4658), Table 8.

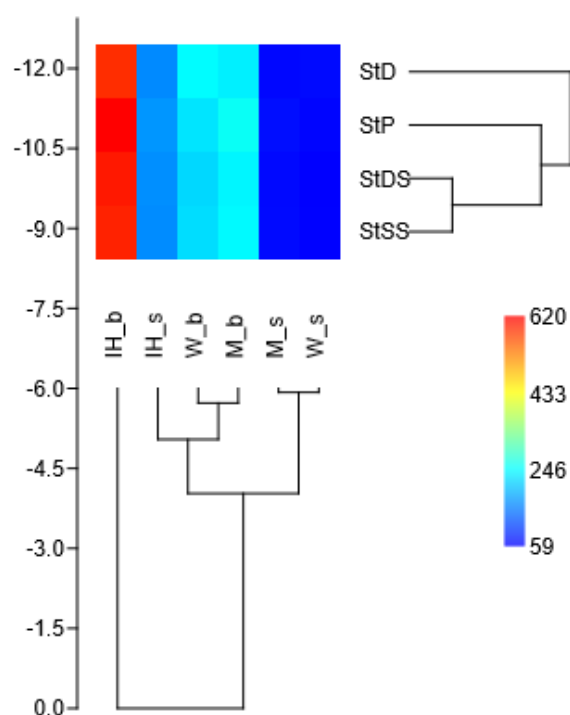
Table 7. The score of soil tillage variants in relation to the main components

	PC 1	PC 2	PC 3
StD	-2.5282	1.0682	0.0726
StSS	-0.1274	-0.8491	-0.4965
StDS	0.1409	-1.3242	0.3983
StP	2.5148	1.1051	0.0256

Table 8. Loading values of given crop variants in relation to the principal components

	PC 1	PC 2	PC 3
W_b	-0.2875	0.6342	0.0473
M_b	0.4565	0.2317	-0.4482
IH_b	0.4686	0.1442	0.4920
W_s	-0.2604	0.6641	0.0697
M_s	0.4523	0.2396	-0.5258
IH_s	0.4658	0.1580	0.5230

The cluster analysis (Two-way) simultaneously grouped the soil work variants and agricultural crops in relation to the amount of carbon sequestered and graphically showed, on a color scale, the most suitable combinations in relation to the amount of carbon sequestered (Coph.corr. = 0.959), Figure 7.

**Figure 7.** Cluster dendrogram based on sequestered carbon in relation to soil works and agricultural crops

Under the study conditions, with chernozem soil and a non-irrigated system, the three crops, wheat, corn and industrial hemp, differentially fixed carbon in biomass and soil, according to experimental data.

The amount of carbon sequestered in wheat soil varied in relation to soil tillage between 59 t ha⁻¹ (StDS) and 66 t ha⁻¹ (StD), with differences without statistical certainty. Wheat, a crop with a fasciculated root system,

explores a smaller volume of soil, and in soil conditions with good fertility, well structured, does not require deep soil tillage (Sui et al., 2024). In order to conserve water in the soil, shallow tillage for wheat cultivation was reported as the most suitable method, given that the yield level was at the level of other deeper tillage methods, and the costs were much lower (Sharifnasab et al., 2024).

In the case of corn, the amount of carbon sequestered varied in relation to soil tillage, between 64 t ha⁻¹ (StD) and 69 t ha⁻¹ (StP), with differences without statistical certainty. Corn has a deep, extensive and strongly developed root system, with a high density of distribution in the soil, so it makes good use of the lands prepared by deep soil tillage (Bray and Topp, 2018; Lu et al., 2025).

Industrial hemp facilitated soil carbon sequestration in amounts ranging from 160 t ha⁻¹ (StD) to 169 t ha⁻¹ (StP), with statistically insignificant differences compared to soil tillage. Industrial hemp has a root system consisting of a fusiform taproot (main root), with numerous fibrous lateral branches (McGrail et al., 2025). Through its specific root system, industrial hemp makes good use of deep soil workings, water and nutrients in the soil, in relation to biomass yield and fiber quality (Miller, 2022; Panday et al., 2026).

Comparative analysis between the crops in this experiment, industrial hemp provided the highest amount of fixed carbon, more than double that of wheat and corn, with differences within statistical safety conditions ($p < 0.01$, T9; $p < 0.001$, T10, T11, and T12). Compared to wheat, industrial hemp sequestered a higher amount of carbon, from 2.42 times higher in the StD variant, to 2.78 times higher in the StDS variant. Compared to corn, industrial hemp sequestered a higher amount of carbon, from 2.45 times higher in the StSS and StP variants, to 2.52 times higher in the StDS variant.

CONCLUSIONS

Under experimental conditions, the three crops, wheat, corn, and industrial hemp, generated variable amounts of carbon sequestered in the soil in relation to soil tillage variants and specific biological potential.

In relation to soil tillage, differences were recorded for each crop, but without statistical certainty. However, for each crop, those that facilitated a higher amount of carbon sequestration were highlighted, namely for wheat the StD variant, for corn and hemp the StP variant.

The comparative analysis between crops highlighted industrial hemp with the highest amounts of sequestered carbon under the study conditions, with statistical certainty at the $p < 0.01$ level (T9) and $p < 0.001$ in the case of the other variants (T10, T11, T12).

Under irrigated crop system conditions, it is possible that sequestered carbon values may change, to be higher for each crop, as a result of better vegetation conditions, synthesized biomass and the functionality of the soil-plant relationship at a different level of intensity.

The results recorded are important from a carbon agriculture perspective, and provide useful information for research, agricultural practice and provide a decision-support information package for farm management.

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