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A COMPARATIVE STUDY OF CARBON FARMING AND CONVENTIONAL SYSTEMS IN CORN AND SUNFLOWER CULTIVATION: CASE STUDY IN NORTH MACEDONIA

Biljana Balabanova[1*], Verica Ilieva[1], Sasa Mitrev[1], Blagoja Mukanov[2], Mario Petkovski[2], Jovana Milosavljeva[2]

[1]*Faculty of Agriculture, Goce Delcev University, Stip, Krste Misirkov 10-A, 2000 Stip, Republic of North Macedonia*
[2]*AgFutura Technologies, Franklin Ruzvelt 6/2-33, 1000, Skopje, Republic of North Macedonia*

*Corresponding author: biljana.balabanova@ugd.edu.mk

Abstract

This study conducts a comparative evaluation of carbon farming versus conventional agricultural systems in corn (*Zea mays L.*) and sunflower (*Helianthus annuus L.*) cultivation, examining their impacts on soil carbon and nitrogen dynamics alongside other soil properties during the 2024–2025 growing season. Soil samples were collected at three critical stages—vegetation onset, midseason, and harvest—to quantify total organic carbon (TOC) and total nitrogen (TN) under each management regime.

Results reveal that carbon farming consistently and significantly enhanced TOC and TN compared to conventional agriculture. In corn plots, carbon farming induced a progressive accumulation of both TOC and TN, driven by increased organic matter inputs and stimulated microbial activity—trends consistent with established organic amendment outcomes. Sunflower plots exhibited a delayed but notable increase in soil C and N, likely reflecting the crop's high nutrient uptake and distinct biomass turnover patterns.

Conversely, conventional management displayed stable or declining TOC and TN trends, underscoring the adverse impacts of reliance on synthetic inputs on soil fertility . These findings highlight carbon farming's effectiveness in enhancing soil health by improving nutrient retention and increasing organic matter, aligning with climate-adaptive and regenerative agriculture principles.

In summary, carbon farming presents a promising strategy for boosting soil carbon and nitrogen stocks in cereal and oilseed production systems, offering co-benefits for soil fertility and climate mitigation. Its implementation may advance sustainable crop production and long-term soil resilience.

Key words: *carbon farming, conventional agriculture, soil organic carbon, total nitrogen, corn, sunflower, agroecological practices, soil fertility, climate-adaptive agriculture, sustainable soil management.*

INTRODUCTION

Carbon serves as a vital indicator of soil health in agroecological systems, reflecting the intricate interplay between soil organic matter (SOM), microbial activity, and overall soil functionality (Bienes et al., 2021; Lal et al., 2021; Bhattacharyya et al., 2022). Monitoring carbon levels provides insights into soil fertility, structure, and resilience, all of which are essential for sustainable agricultural practices (Davis et al., 2017). SOM, primarily composed of decomposed plant and animal material, is a key component of soil carbon (Merckx et al., 2001; Lorenz et al., 2018; Javed et al., 2022). Its presence enhances soil aggregation, leading to improved soil structure. Well-aggregated soils have better porosity, facilitating root penetration and water infiltration, which are crucial for plant growth and resilience to droughts (Qi et al., 2022). Additionally, improved soil structure reduces erosion and nutrient leaching, promoting long-term soil fertility (Bronick & Lal, 2005; Ramesh et al., 2019). Carbon-rich soils have improved water-holding capacity, which is vital for maintaining crop health during dry periods (Usharani et al., 2019). Enhanced water retention reduces the need for frequent irrigation and helps maintain soil moisture levels, contributing to more resilient agricultural systems (Adhikari et al., 2022; Song et al., 2023). Soil carbon contributes to the formation of stable aggregates, which protect the soil from erosion. Cover crops and reduced tillage practices increase soil organic matter, further enhancing soil structure and reducing the risk of soil erosion (Triberti et al., 2016; Nayak et al., 2019). This protection preserves the productivity and long-term use of agricultural land.

Agriculture accounts for nearly a quarter of global greenhouse gas emissions, primarily through methane (CH_4) and nitrous oxide (N_2O) emissions, as well as soil carbon losses (Acharya et al., 2022). Conversely, sustainable agricultural practices such as no-till farming, cover cropping, and agroforestry can sequester significant amounts of carbon in soils and biomass (Meena et al., 2020; Nicoloso & Rice, 2021). To effectively mitigate climate change, it is imperative to establish reliable benchmarks for carbon sequestration in agricultural systems. Several findings indicate that carbon farming practices lead to higher SOC levels compared to conventional methods. For instance, a meta-analysis of cover crop responses in corn systems revealed an average SOC increase of 7.3 % (Joshi et al., 2023). Similarly, studies in Brazil showed that no-tillage systems combined with cover crops resulted in higher carbon stocks and increased maize yields (Besen et al., 2024). The increased SOC in carbon farming systems can enhance soil fertility, water retention, and enhance resiliencies to extreme weather events. However, the effectiveness of these practices can vary based on factors such as soil type, climate, and management techniques (Paustian et al., 2019; Coonan et al., 2020; Dupla et al., 2024). Further research is needed to optimize these practices for different agricultural contexts. Adopting carbon farming practices in corn and sunflower cultivation can significantly contribute to soil carbon sequestration and promote sustainable agriculture (Andries et al., 2021). While challenges remain, the potential benefits underscore the importance of integrating these practices into mainstream farming systems.

Historically, the Green Revolution introduced high-yielding varieties and intensive input use, significantly boosting cereals production (Khush, 1999; Pingali, 2017). However, these methods often led to environmental concerns, including soil erosion, nutrient depletion, and increased greenhouse gas emissions. Consequently, contemporary agricultural research emphasizes integrated approaches that balance productivity with environmental stewardship. Key strategies for improving corn farming encompass: 1) Crop rotation and intercropping including implementing diverse cropping systems, such as maize-legume rotations, enhances soil fertility and reduces pest pressures; 2) Conservation tillage: adopting no-till practices preserves soil structure, mitigates erosion, and sequesters carbon; 3) Nutrient management with optimizing fertilizer application, including the use of green ammonia, reduces emissions and improves nutrient use efficiency; 4) Biological control and integrated pest management utilizinging biopesticides and IPM strategies curtails reliance on chemical inputs and promotes ecological balance. These practices not only bolster corn yields but also contribute to environmental sustainability (Nsabiyeze et al., 2024).

Establishing robust benchmarks for carbon sequestration in agriculture is crucial for evaluating the effectiveness of carbon farming practices and achieving climate mitigation goals. By integrating diverse methodologies and addressing existing uncertainties, the proposed framework offers a pathway towards reliable and scalable carbon quantification in agricultural systems (Avasiloaie et al., 2023). Monitoring and enhancing soil carbon levels are fundamental for assessing and improving soil health in agroecological systems (Oldfield et al., 2022). Practices that increase soil organic matter, such as agroforestry, cover cropping, and reduced tillage, not only sequester carbon but also bolster soil structure, fertility, and resilience (Rumpel et al., 2020; Smith et al., 2020; Tiefenbacher et al., 2021; Kyriakarakos et al., 2024). These benefits emphasize the significance of carbon as a central indicator of soil health and a fundamental element of sustainable agriculture.

MATERIAL AND METHODS

Field activity overview

In 2024, a series of field activities were undertaken to assess the effectiveness of different agricultural practices on soil health and carbon sequestration. The experimental setups included corn and sunflower crops. The field for each crop was divided into two sub-plots (0.25 hectares for conventional production and 0.25 hectares for carbon farming). Conventional corn production involved sowing it as a sole crop. The carbon farming plot used the sowing of beans between corn rows as an intercrop for natural nitrogen fixation. The sowing of corn, beans and sunflower, in both conventional and carbon production, was carried out on 12.04.2024. On sunflower plots, conventional production used sowing sunflower as a sole crop. For the carbon farming plot, sunflower sowing was carried out with the application of a cover crop. Before sowing and after the emergence of the sunflower, a biostimulator was applied using a drone.

A2 (Corn + Beans): This intercropping system aimed to enhance biodiversity and soil nutrient cycling. Regular irrigation was implemented to support early growth.

A3 (Corn): Conventional corn cultivation was practiced, focusing on standard agronomic practices. Irrigation was applied as needed to maintain optimal growth conditions.

A4 (Sunflower): Sunflower seeds were sown, with attention to spacing and depth to ensure uniform emergence. Irrigation was carefully managed to promote optimal plant growth and development.

A5 (Sunflower + Cover Crop): Sunflower planting was complemented with a cover crop (winter barley), to enhance soil organic matter and prevent erosion. Irrigation practices were adjusted to support both crops effectively.

Throughout this period, soil moisture levels were monitored, and necessary adjustments to irrigation schedules were made to accommodate the varying water requirements of each system. By August, all crops had reached full growth and midpoint assessments of soil agrochemical properties and carbon footprint estimates were conducted. After harvesting all crops in October, post-harvest residues were ploughed into the soil. The sunflower carbon production plot was sown with winter barley as a cover crop on 20.11.2024 and the winter barley was plowed into the soil on 26.03.2025, at the booting stage. Final assessments were conducted in May 2025.

A2 (Corn + Beans): Harvesting was performed for both corn and beans. Immediately after harvest, in October 2024, post-harvest residues were plowed, and in May 2025, soil samples were collected to analyze the impact of intercropping on soil carbon content.

A3 (Corn): Corn was harvested following standard procedures. After harvest, in October 2024, the post-harvest residues were plowed, and in May 2025, soil sampling was conducted to assess the effects of conventional practices on soil health.

A4 (Sunflower): Sunflowers were harvested, and after harvest in October 2024, post-harvest residues were plowed into the soil, and in May 2025, soil samples were taken to evaluate the influence of monoculture on soil properties.

A5 (Sunflower + Cover Crop): The sunflowers were harvested according to standard procedures and post-harvest residues were immediately plowed into the soil. The cover crop was sown on 20.11.2024, and incorporated into the soil on 26.03.2025. Soil samples were collected in May 2025, to determine the benefits of cover cropping on soil organic matter and carbon sequestration.

Soil samples were collected from multiple representative sites under agricultural land use. Sampling followed a stratified approach, accounting for variables such as crop type, fertilizer application history, inclusion of intercrops, cover crops and soil texture. At each site, composite samples were taken from the top 0-20 cm layer using a soil auger and stored in labeled polyethylene bags for laboratory analysis.

Table 1. General overview of the applied cultivation practices.

Setup	Crop(s)	Practice type	Start-point (April, 2024)	Mid-point (August, 2024)	End-point (May 2025)
A2	Corn + Beans	Carbon Farming	Sowing & Irrigation	Fertilizer (biostimulator)	Residue management, Intercrop
A3	Corn	Conventional	Sowing & Irrigation	Fertilizer (mineral)	Residue management
A4	Sunflower	Conventional	Sowing & Irrigation	Fertilizer (mineral)	Residue management
A5	Sunflower + Cover Crop	Carbon Farming	Sowing & Irrigation	Fertilizer (biostimulator)	Residue management, cover crop

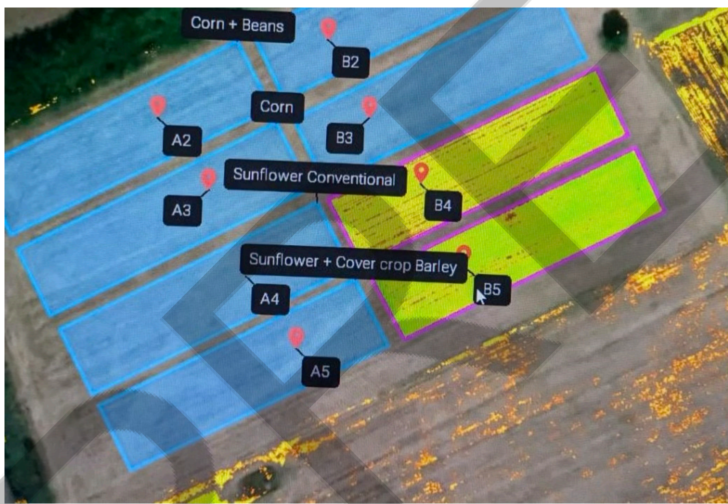

Figure 1. Field setup for the experiments: A2 (Corn + Beans) – Carbon farming; A3 (Corn) – Conventional; A4 (Sunflower) – Conventional; A5 (Sunflower + Cover Crop) – Carbon farming.

Agrochemical soil characterization

Agrochemical determination of soil typically outlines the procedures used to analyze key soil parameters related to fertility. To assess the agrochemical properties of the soil, a series of standardized laboratory analyses were conducted. Each soil sample was air-dried, ground, and passed through a 2 mm sieve prior to testing.

Soil pH and electrical conductivity (EC) were determined using aqueous soil suspensions. For pH measurement, a 1:2.5 soil-to-water ratio (weight/volume) was prepared and allowed to equilibrate before being analyzed with a calibrated digital pH meter. For EC, a separate suspension was made using a 1:5 soil-to-water ratio and measured using a conductivity meter to evaluate the soluble salt content of the soil.

Organic matter content was estimated using the Walkley-Black method, which involves the oxidation of organic carbon by potassium dichromate in the presence of sulfuric acid. The unreacted dichromate was then titrated to determine the amount of oxidized carbon, which was used to calculate the organic matter percentage.

Total nitrogen (N) content in the soil was determined by the Kjeldahl method. This procedure includes the digestion of the soil sample with concentrated sulfuric acid in the presence of a catalyst to convert organic nitrogen into ammonium. The digest was then subjected to alkaline distillation, and the released ammonia was trapped and quantified through titration.

Available phosphorus (P) was measured based on soil reaction type. The Olsen method was applied for neutral to alkaline soils, utilizing a sodium bicarbonate extractant. For acidic soils, the Bray-1 method was used. In both methods, the phosphorus in the extract was quantified colorimetrically using a spectrophotometer, based on the formation of a phosphomolybdenum blue complex.

Exchangeable potassium (K) was extracted from the soil using 1M ammonium acetate solution. The potassium content in the extract was then quantified using either flame photometry or atomic absorption spectrophotometry (AAS), depending on the available instrumentation.

These methods collectively provided key insights into the fertility and chemical status of the soils under study, contributing to a comprehensive understanding of their suitability for agricultural use.

Soil carbon analysis – comparative validation

Soil organic matter was quantified using both the traditional Walkley-Black (WB) method and a modified spectrophotometric variant to improve sensitivity and analytical precision.

The Walkley-Black method is a classical wet oxidation technique that estimates soil organic carbon through chemical oxidation (Balabanova et al., 2024). In this method, a known amount of finely ground soil was treated with an excess of potassium dichromate ($K_2Cr_2O_7$) solution and concentrated sulfuric acid (H_2SO_4). The exothermic reaction generates sufficient heat to oxidize the organic carbon present in the soil sample. After a reaction period, the remaining unreacted dichromate was titrated with ferrous sulfate solution. The amount of dichromate reduced during the reaction is stoichiometrically related to the amount of oxidized organic carbon, which is then used to calculate organic matter content.

To improve sensitivity and detection, especially in soils with low organic content, the Modified Walkley and Black method was also employed. This variation follows the same principle of dichromate oxidation but replaces the titrimetric endpoint with spectrophotometric detection. After the oxidation reaction, the resulting chromate solution is analyzed using a UV-Vis spectrophotometer, typically at a wavelength around 600 nm, corresponding to the absorbance of the Cr^{3} complex formed. This modification allows for more precise quantification of organic carbon, particularly in samples with low or variable organic matter, by reducing operator subjectivity and enhancing sensitivity.

By applying both methods, a comparative analysis of the accuracy and efficiency of classical versus modern detection techniques was achieved, ensuring robustness and reliability in the determination of soil organic matter.

Data collection and model application

To comprehensively evaluate the agrochemical profile of the soil and its associated environmental impact, a structured approach combining field data collection with model-based analysis was adopted. The study focused on characterizing key soil agrochemical parameters and estimating the carbon footprint resulting from agricultural inputs and practices. Integrating chemical characterization of soil with carbon footprint analysis, this approach provided a holistic view of both soil fertility and the environmental sustainability of agricultural practices, guiding more efficient and climate-conscious land management decisions. The key components included: Soil carbon fluxes, influenced by organic matter levels and land management practices.

RESULTS AND DISCUSSION

Climate variables such as temperature and precipitation significantly affect SOC dynamics. Warmer temperatures accelerate organic matter decomposition, potentially reducing SOC levels, while increased precipitation can enhance plant growth and organic matter input, promoting

SOC accumulation. These climatic factors interact with soil properties to influence overall soil health and carbon storage capacity. The field experiment aimed to compare the impacts of conventional farming and carbon farming practices on soil health and environmental performance, specifically for corn (*Zea mays*) and sunflower (*Helianthus annuus*) cultivation. The comparison was structured around two key analytical dimensions: soil agrochemical properties and carbon footprint assessments.

Agrochemical analysis outputs

The analysis of soil agrochemical parameters, specifically pH (KCl), pH (H_2O), total nitrogen (N), available phosphorus (P_2O_5), and potassium (K_2O), provided valuable insight into the impact of carbon farming practices compared to conventional agriculture for corn and sunflower cultivation during the 2024–2025 growing season. Measurements were taken at three key stages: the start of the experiment (April, 2024), mid-point (August, 2024), and end-point (May, 2025), allowing for a comparative temporal and treatment-based assessment.

Across both crops, soils managed under carbon farming practices showed notable trends in terms of nutrient retention and soil quality stabilization. For corn, carbon farming plots exhibited a gradual increase or maintenance of total nitrogen levels, in contrast to the more fluctuating and sometimes declining trends observed under conventional practices. This suggests that the application of organic amendments commonly associated with carbon farming may enhance nitrogen preservation through improved microbial activity and reduced leaching.

Phosphorus (P_2O_5) and potassium (K_2O) levels were generally higher or more stable in carbon farming systems over both years. In contrast, conventional plots showed greater year-to-year variability, likely due to standard fertilization regimes combined with increased nutrient runoff and lower organic matter retention. These findings are consistent with other studies emphasizing the nutrient buffering capacity of carbon-enriched soils.

Soil pH values remained within optimal agronomic ranges in all plots; however, a slight acidification trend was observed in conventional systems, particularly in sunflower cultivation, as reflected in decreasing pH (KCl) values from 2024 to 2025. This could be attributed to the continuous application of mineral fertilizers, which are known to gradually lower soil pH. In contrast, carbon farming plots maintained more stable pH values, suggesting a buffering effect from increased organic matter content and lower synthetic input intensity.

For sunflower, similar patterns were observed, with carbon farming systems showing a consistent or improved soil nutrient profile over time, particularly in nitrogen and potassium content. Notably, the mid-point measurements in 2024 captured an increase in nutrient availability in carbon farming plots, possibly reflecting cumulative improvements in soil structure and biological activity as a result of sustainable practices such as organic fertilization and the introduction of intercropping.

Total nitrogen (N) is a critical indicator of soil fertility, directly influencing plant growth and productivity. The monitoring of total nitrogen levels over the vegetation period under different agricultural management practices, carbon farming versus conventional farming, in corn and sunflower cropping systems provides important insight into how farming practices impact long-term soil nutrient dynamics and sustainability. At the start point of the measurement period, nitrogen content across both carbon farming and conventional plots was comparable, reflecting similar baseline soil fertility levels. However, divergent trends emerged over time. In the carbon farming plots, total nitrogen content showed a gradual increase or remained stable between mid-point and end-point of measurements. This trend can be attributed to the incorporation of organic matter and improved microbial activity, all of which promote nitrogen mineralization and retention in the root zone (Figures 2a and 2b).

By contrast, in conventional corn plots, nitrogen levels exhibited a declining trend, especially between the mid-point (2024) and end-point (2025) measurements. The decrease is likely due to the use of synthetic nitrogen fertilizers, which may lead to higher rates of nitrogen leaching or volatilization in the absence of sufficient organic matter to retain and buffer nutrients.

Table 2. Overall agrochemical soil characteristics.

Start-point	pH(KCl)	pH(H2O)	EC (mS/cm)	Total N mg/g	P2O5 (mg/100g)	K2O (mg/100g)	SOM (%)
A2	7.56	8.43	0.53	1.15	29.9	57.4	7.93
A3	7.66	8.43	0.50	1.36	47.8	71.3	7.59
A4	7.54	8.45	0.51	1.19	40.4	51.8	7.12
A5	7.55	8.46	0.51	1.34	33.5	47.2	7.02
Mid-point	**pH(KCl)**	**pH(H2O)**	**EC (mS/cm)**	**Total N (mg/g)**	**P2O5 (mg/100g)**	**K2O (mg/100g)**	**SOM (%)**
A2	8.55	7.74	0.54	1.31	41.59	99.64	1.95
A3	8.63	7.78	0.41	0.79	37.13	80.09	1.94
A4	8.57	7.76	0.46	0.82	39.39	68.82	1.71
A5	8.51	7.75	0.65	0.93	39.98	69.57	1.56
End-point	**pH(KCl)**	**pH(H2O)**	**EC (mS/cm)**	**Total N (mg/g)**	**P2O5 (mg/100g)**	**K2O (mg/100g)**	**SOM (%)**
A2	8.71	7.81	0.50	1.03	39.27	73.63	2.42
A3	8.79	7.85	0.45	0.86	39.08	67.85	2.32
A4	8.68	7.81	0.44	1.37	40.11	72.18	1.96
A5	8.77	7.79	0.43	1.77	48.88	73.19	2.05

In the sunflower plots, a similar pattern was observed. Carbon farming systems maintained relatively stable or slightly increasing total nitrogen content over the two-year period. The application of regenerative practices, such as the introduction of cover crops and organic inputs, likely contributed to enhanced nitrogen conservation, consistent with carbon sequestration goals. Conversely, conventional sunflower fields showed a more pronounced decrease in total nitrogen, particularly in mid-point assessments. This decline may be exacerbated by sunflower's relatively high nitrogen demand during flowering (Reproductive stage R5, according to the system of phenological phases according to Schneiter and Miller 1981), and - seed formation R6 (anthesis complete), which, under conventional systems, may not be replenished adequately through mineral fertilization alone. The absence of organic matter recycling and microbial support mechanisms further limits nitrogen retention.

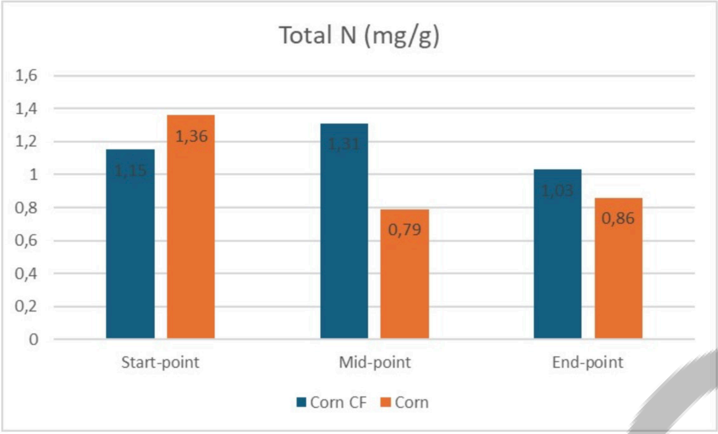

Figure 2a. Nitrogen content in soil, along the vegetation period Carbon farming vs. conventional practices (corn case study), CF – carbon farming.

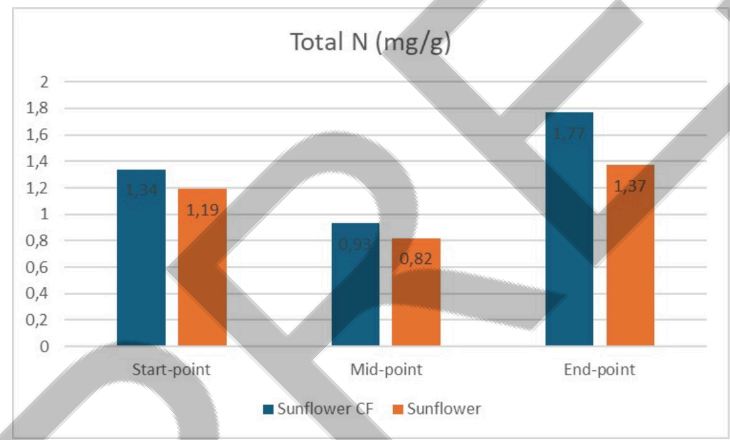

Figure 2b. Nitrogen content in soil, along the vegetation period Carbon farming vs. conventional practices (sunflower case study), CF – carbon farming.

The comparative trends clearly indicate that carbon farming practices are more effective in maintaining or improving soil nitrogen levels over time, compared to conventional systems that tend to deplete nitrogen reserves. The long-term retention of nitrogen in carbon farming systems is critical not only for maintaining crop yields but also for enhancing soil health, promoting microbial biodiversity, and reducing environmental impacts such as nitrate leaching into groundwater. These findings underscore the importance of integrating organic matter inputs and conservation management techniques in nitrogen-sensitive cropping systems such as corn and sunflower. Sustained improvements in total nitrogen under carbon farming contribute to the broader goals of increasing the level of agroecosystem resilience and climate-smart agriculture.

Carbon footprint and soil carbon measurements

Organic matter is the primary reservoir of soil organic carbon (SOC), and its accumulation is directly linked to the potential of soil to function as a long-term carbon sink. In this study, the temporal dynamics of OM were monitored across corn and sunflower systems under both carbon farming and conventional practices from start-point to end-point of measurement, providing valuable insight into the processes of soil carbon stabilization and loss. In the corn plots managed under carbon farming, total organic matter showed a steady increasing trend across all three measurement points. This increase is a clear indication of successful carbon sequestration. The application of intercropping, cover crop and organic soil amendments contributed to the accumulation of plant residues and microbial biomass in the upper soil layers. These inputs not only directly add organic carbon but also foster a microenvironment that enhances humus formation and slows down organic matter decomposition.

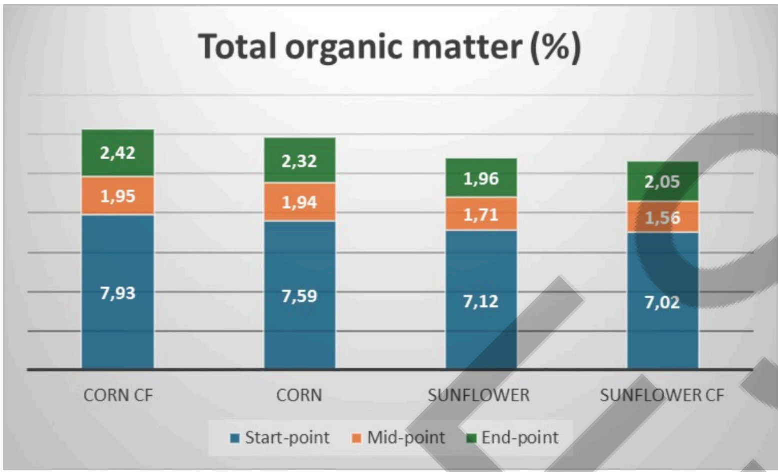

Figure 3. Total organic matter in experimental fields, carbon farming vs. conventional farming, CF – carbon farming.

In the plots under carbon farming, total organic matter initially decreased from April 2024 to August 2024, but then increased by the 2025 end-point (Figure 3). This initial decline could be attributed to several crop-specific and management-related factors. Sunflower is known for its deep rooting system and high nutrient demand, especially nitrogen and potassium, which can deplete the organic matter pool in the early growth stages. Additionally, decomposition of previously applied organic materials or transition from conventional to regenerative practices may result in a temporary imbalance between organic matter inputs and microbial decomposition rates.

By 2025, the observed increase in organic matter under carbon farming can be linked to improved soil structure and higher biomass return to the soil after harvest. The cumulative effect of residue retention and microbial activity leads to better humification of organic inputs, allowing the soil to recover and sequester more carbon over time.

In conventional plots, the organic matter trend remained flat or slightly declining, indicating limited capacity for carbon accumulation. The absence of systemic organic inputs and soil conservation practices hampers the replenishment of soil carbon, especially after high-demand crops like sunflower. The findings from both crop systems show a strong positive correlation between total organic matter and carbon sequestration potential. In carbon farming systems, increased TOM reflects enhanced biological activity, greater biomass input, and improved physical conditions that favor long-term carbon storage. Conversely, conventional practices tend to either deplete or stagnate organic matter levels, limiting the soil's ability to sequester carbon. As the primary component of soil organic matter, TOC is directly linked to soil fertility, microbial activity, and carbon sequestration potential. TOC was measured across corn and sunflower plots managed under both carbon farming and conventional practices. The temporal trends reveal important distinctions between the two management systems and their impact on carbon dynamics in agricultural soils. In corn plots managed with carbon farming practices, TOC levels showed a consistent and significant increase in 2024 and remained elevated through 2025. This trend reflects the cumulative benefits of regenerative practices such as organic residue incorporation, intercropping and cover cropping, all of which contribute to both the addition and stabilization of organic carbon in the soil. Enhanced soil aggregation and microbial biomass formation under these systems likely contributed to the retention of newly added carbon, leading to a steady buildup of TOC. In contrast, conventional corn plots demonstrated either minimal increases or stagnant TOC levels, with minor fluctuations over the two years. This stagnation can be attributed to low organic input levels, and the reliance on synthetic fertilizers, which do not contribute organic carbon and may accelerate the mineralization of existing soil organic matter. As a result, the soil under conventional management exhibits limited capacity to sequester carbon in the long term.

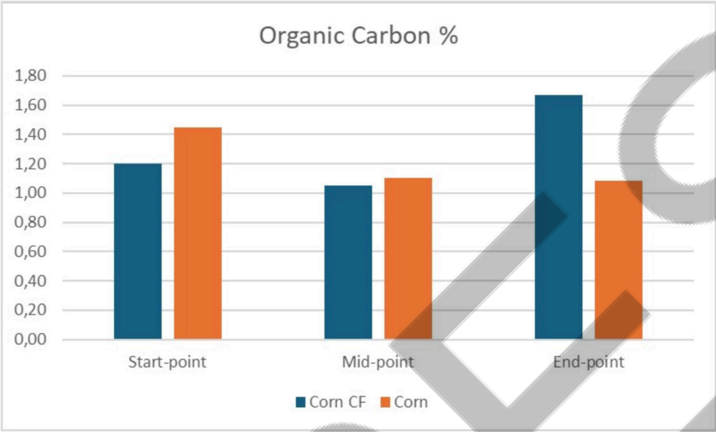

Figure 4. Total organic carbon for pilot corn cultivation, CF – carbon farming.

In sunflower plots under carbon farming, TOC levels also increased in 2024, and remained elevated in 2025, though the magnitude of change was slightly more gradual compared to corn. This pattern may be explained by the higher nutrient and carbon demands of sunflower, which can slow initial organic carbon accumulation, particularly in soils transitioning from conventional to regenerative practices. However, as the carbon farming system matures and stabilizes, the rate of carbon input from plant residues and microbial activity begins to exceed decomposition rates, leading to a net increase in TOC. On the other hand, conventional sunflower plots exhibited relatively static TOC levels with no significant upward trend. The absence of organic amendments and the lack of soil conservation practices reduce the opportunity for carbon input and stabilization, highlighting the limitations of conventional management in supporting carbon sequestration, particularly for high-demand crops like sunflower.

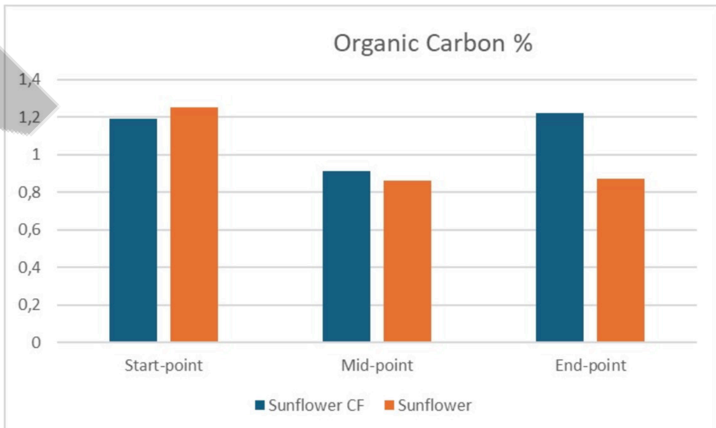

Figure 5. Total organic carbon for pilot sunflower cultivation, CF – carbon farming.

The experimental findings clearly demonstrate that carbon farming practices enhance total organic carbon content in agricultural soils for both corn and sunflower systems. The sustained increase in TOC over the two-year period under carbon farming reflects the effectiveness of these systems in promoting carbon storage, improving soil resilience, and mitigating climate change impacts. Importantly, the maintenance of elevated TOC levels at the end of the study (2025) suggests that carbon farming not only boosts carbon input but also creates the conditions necessary for long-term carbon stabilization, including increased microbial activity, better aggregation, and reduced soil erosion. These findings are in agreement with extensive literature that underscores the pivotal role of organic carbon in sustainable soil management. The distinction between the steady carbon gains in carbon farming and the stagnation in conventional systems underscores the need for widespread adoption of regenerative practices to enhance carbon sequestration and overall soil quality in intensive cropping systems.

CONCLUDING REMARKS

This study demonstrates the substantial benefits of carbon farming practices over conventional systems in enhancing soil health, improving agrochemical properties, and increasing carbon sequestration in corn and sunflower cropping systems. Over the 2024–2025 growing seasons, soils under carbon farming management exhibited more stable and favorable trends in total nitrogen, available phosphorus, and potassium content, alongside improved pH buffering capacity. In terms of carbon dynamics, carbon farming significantly increased total organic matter (TOM) and total organic carbon (TOC) across both crop systems. The observed gains in TOC reflect the cumulative effect of enhanced biomass input, improved soil structure, and greater microbial activity under regenerative management. Notably, while TOC and TOM levels in conventional plots remained static or declined, carbon farming plots showed sustained and measurable increases, indicating a superior capacity for long-term carbon storage and soil resilience.

The evidence from this field experiment underscores the crucial role of carbon farming in advancing climate-smart agriculture. By promoting nutrient stability, enhancing soil organic carbon stocks, and reducing environmental degradation, carbon farming practices offer a viable pathway to more sustainable and resilient agroecosystems. The findings support the broader adoption of regenerative techniques to mitigate soil degradation, support food security, and contribute meaningfully to climate change mitigation through agricultural carbon sequestration.

Overall, the results demonstrate that carbon farming has the potential to enhance soil fertility and stability over time, compared to conventional agriculture. The ability to maintain or improve agrochemical soil parameters over multiple growing seasons suggests not only environmental benefits but also agronomic sustainability. These findings highlight the critical importance of long-term soil monitoring for assessing the effectiveness of regenerative agricultural practices, especially within the framework of climate-smart and carbon-sequestering strategies.

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REFERENCES

Acharya, U., Lal, R., & Chandra, R. (2022). Data driven approach on in-situ soil carbon measurement. *Carbon Management*, 13(1), 401-419.

Adhikari, S., Timms, W., & Mahmud, M. P. (2022). Optimising water holding capacity and hydrophobicity of biochar for soil amendment–A review. *Science of The Total Environment*, 851, 158043.

Andries, A., Morse, S., Murphy, R. J., Lynch, J., Mota, B., & Woolliams, E. R. (2021). Can current earth observation Technologies provide useful information on soil organic carbon stocks for environmental land management policy?. *Sustainability,* 13(21), 12074.

Avasiloaiei, D. I., Calara, M., Brezeanu, P. M., Gruda, N. S., & Brezeanu, C. (2023). The evaluation of carbon farming strategies in organic vegetable cultivation. *Agronomy,* 13(9), 2406.

Balabanova, B., Ilieva, V., Mitrev, S., Ristovska, N., Mukanov, B., Jankuloska, V., ... & Milosavljeva, J. (2024). Comparative cost analysis of soil carbon determination using toc analyzer vs. Walkley-Black method. *Journal of Agriculture and Plant Sciences,* 22(2), 15-24.

Besen, M. R., Ribeiro, R. H., Bratti, F., Locatelli, J. L., Schmitt, D. E., & Piva, J. T. (2024). Cover cropping associated with no-tillage system promotes soil carbon sequestration and increases crop yield in Southern Brazil. *Soil and Tillage Research*, 242, 106162.

Bhattacharyya, S. S., Ros, G. H., Furtak, K., Iqbal, H. M., & Parra-Saldívar, R. (2022). Soil carbon sequestration–An interplay between soil microbial community and soil organic matter dynamics. *Science of The Total Environment*, 815, 152928.

Bienes, R., Marques, M. J., Sastre, B., García-Díaz, A., Esparza, I., Antón, O., et al. (2021). Tracking changes on soil structure and organic carbon sequestration after 30 years of different tillage and management practices. *Agronomy,* 11(2), 291.

Bronick, C. J., & Lal, R. (2005). Soil structure and management: a review. *Geoderma,* 124(1-2), 3-22.

Coonan, E. C., Richardson, A. E., Kirkby, C. A., Kirkegaard, J. A., Amidy, M. R., & Strong, C. L. (2020). Soil fertility and nutrients mediate soil carbon dynamics following residue incorporation. *Nutrient Cycling in Agroecosystems*, 116(2), 205-221.

Davis, M. R., Alves, B. J., Karlen, D. L., Kline, K. L., Galdos, M., & Abulebdeh, D. (2017). Review of soil organic carbon measurement protocols: A US and Brazil comparison and recommendation. *Sustainability,* 10(1), 53.

Dupla, X., Bonvin, E., Deluz, C., Lugassy, L., Verrecchia, E., Baveye, P. C., ... & Boivin, P. (2024). Are soil carbon credits empty promises? Shortcomings of current soil carbon quantification methodologies and improvement avenues. *Soil Use and Management*, 40(3), e13092.

Javed, A., Ali, E., Afzal, K. B., Osman, A., & Riaz, S. (2022). Soil fertility: Factors affecting soil fertility, and biodiversity responsible for soil fertility. International *Journal of Plant, Animal and Environmental Sciences*, 12(1), 21-33.

Joshi, D. R., Sieverding, H. L., Xu, H., Kwon, H., Wang, M., Clay, S. A., ... & Clay, D. E. (2023). A global meta-analysis of cover crop response on soil carbon storage within a corn production system. *Agronomy Journal,* 115(4), 1543-1556.

Khush, G. S. (1999). Green revolution: preparing for the 21st century. *Genome*, 42(4), 646-655.

Kyriakarakos, G., Petropoulos, T., Marinoudi, V., Berruto, R., & Bochtis, D. (2024). Carbon Farming: Bridging Technology Development with Policy Goals. *Sustainability*, 16(5), 1903.

Lal, R., Monger, C., Nave, L., & Smith, P. (2021). The role of soil in regulation of climate. *Philosophical Transactions of the Royal Society* B, 376(1834), 20210084.

Lorenz, K., Lal, R., Lorenz, K., & Lal, R. (2018). Soil carbon stock. *Carbon sequestration in agricultural ecosystems*, 39-136.

Meena, R. S., Kumar, S., & Yadav, G. S. (2020). Soil carbon sequestration in crop production. *Nutrient dynamics for sustainable crop production*, 1-39.

Merckx, R., Diels, J., Vanlauwe, B., Sanginga, N., Denef, K., & Oorts, K. (2001). Soil organic matter and soil fertility. Sustaining soil fertility in West Africa, 58, 69-89.

Nayak, A. K., Rahman, M. M., Naidu, R., Dhal, B., Swain, C. K., Nayak, A. D., ... & Pathak, H. (2019). Current and emerging methodologies for estimating carbon sequestration in agricultural soils: A review. *Science of the total environment*, 665, 890-912.

Nicoloso, R. S., & Rice, C. W. (2021). Intensification of no-till agricultural systems: An opportunity for carbon sequestration. *Soil Science Society of America Journal*, 85(5), 1395-1409.

Nsabiyeze, A., Ma, R., Li, J., Luo, H., Zhao, Q., Tomka, J., & Zhang, M. (2024). Tackling climate change in agriculture: A global evaluation of the effectiveness of carbon emission reduction policies. *Journal of Cleaner Production*, 142973.

Oldfield, E. E., Eagle, A. J., Rubin, R. L., Rudek, J., Sanderman, J., & Gordon, D. R. (2022). Crediting agricultural soil carbon sequestration. *Science*, 375(6586), 1222-1225.

Paustian, K., Collier, S., Baldock, J., Burgess, R., Creque, J., DeLonge, M., ... & Jahn, M. (2019). Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. *Carbon Managemen*t, 10(6), 567-587.

Pingali, P. L. (2017). The Green Revolution and crop biodiversity. In *Routledge handbook of agricultural biodiversity* (pp. 213-223). Routledge.

Qi, J. Y., Han, S. W., Lin, B. J., Xiao, X. P., Jensen, J. L., Munkholm, L. J., & Zhang, H. L. (2022).

Improved soil structural stability under no-tillage is related to increased soil carbon in rice paddies: Evidence from literature review and field experiment. *Environmental Technology & Innovation,* 26, 102248.

Ramesh, T., Bolan, N. S., Kirkham, M. B., Wijesekara, H., Kanchikerimath, M., Rao, C. S., ... & Freeman II, O. W. (2019). Soil organic carbon dynamics: Impact of land use changes and management practices: A review. *Advances in agronomy,* 156, 1-107.

Rumpel, C., Amiraslani, F., Chenu, C., Garcia Cardenas, M., Kaonga, M., Koutika, L. S., ... & Wollenberg, E. (2020). The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *Ambio,* 49, 350-360.

Schneiter, A.A. and Miller, J.F. (1981). Description of Sunflower Growth Stages. Crop Science, 21, 901-903. https://doi.org/10.2135/cropsci1981.0011183X002100060024x

Smith, P., Soussana, J. F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., ... & Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology,* 26(1), 219-241.

Song, M., Li, J., Gao, L., & Tian, Y. (2023). Comprehensive evaluation of effects of various carbon-rich amendments on overall soil quality and crop productivity in degraded soils. *Geoderma,* 436, 116529.

Tiefenbacher, A., Sandén, T., Haslmayr, H. P., Miloczki, J., Wenzel, W., & Spiegel, H. (2021). Optimizing carbon sequestration in croplands: A synthesis. *Agronomy,* 11(5), 882.

Triberti, L., Nastri, A., & Baldoni, G. (2016). Long-term effects of crop rotation, manure and mineral fertilisation on carbon sequestration and soil fertility. *European Journal of Agronomy*, 74, 47-55.

Usharani, K.V., Roopashree, K. M., & Naik, D. (2019). Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture. *Journal of Pharmacognosy and Phytochemistry,* 8(5), 1256-1267.

КОМПАРАТИВНА СТУДИЈА НА ПРАКТИКИ ЗА ЈАГЛЕРОДНО И КОНВЕНЦИОНАЛНО ОДГЛЕДУВАЊЕ НА ПЧЕНКА И СОНЧОГЛЕД: СТУДИЈА НА СЛУЧАЈ ВО СЕВЕРНА МАКЕДОНИЈА

Биљана Балабанова[1*], Верица Илиева[1], Саша Митрев[1], Благоја Муканов[2], Марио Петковски[2], Јована Милосављева[2]

[1]*Земјоделски факултет, Универзитет „Гоце Делчев", „Крсте Мисирков" 10-А, 2000 Штип, Република Северна Македонија*

[2]*АгФутура Технологии, „Франклин Рузвелт" 6/2-33, 1000 Скопје, Република Северна Македонија*

**Контакт автор:* biljana.balabanova@ugd.edu.mk

Резиме

Оваа студија претставува споредбена евалуација на јаглеродното земјоделство и конвенционалните агроеколошки системи при одгледување на пченка (Zea mays L.) и сончоглед (Helianthus annuus L.), со фокус на нивното влијание врз јаглеродната и азотната динамика во почвата, како и врз други почвени карактеристики во периодот 2024-2025. Почвени примероци беа земани на почетокот, на средината и на крајот од студијата, со цел да се процени вкупната органска материја (TOC) и вкупниот азот (TN) под различни системи на управување.

Резултатите покажаа доследно и значајно зголемување на содржината на јаглерод и азот во почвите третирани според принципите на јаглеродно земјоделство, во споредба со оние под конвенционално управување. Кај пченката, јаглеродното земјоделство доведе до прогресивно акумулирање на TOC и TN, што се припишува на внесот на органска материја и засилената микробна активност. Кај сончогледот исто така беше забележано зголемување на TOC и TN, иако со одложена реакција, најверојатно поради повисоките нутритивни потреби на културата и поголемото враќање на биомаса во почвата.

Наспроти тоа, конвенционалните системи покажаа стагнација или намалување на TOC и TN, што ги потенцира ограничувањата на зависноста од синтетички ѓубрива за одржување на долгорочната плодност на почвата. Овие наоди го нагласуваат потенцијалот на јаглеродното земјоделство како одржлива стратегија за подобрување на здравјето на почвата, зголемување на задржувањето на хранливи материи и придонесување кон климатски прилагодливо земјоделство во производството на житарки и маслодајни култури.

Клучни зборови: *јаглеродно земјоделство, конвенционално земјоделство, органски јаглерод во почвата, вкупен азот, пченка, сончоглед, агро-еколошки практики, почвена плодност, климатски прилагодливо земјоделство, одржливо управување со почвата.*