JOURNAL OF AGRICULTURE AND PLANT SCIENCES, JAPS, Vol 24, No. 1, 2026

Manuscript received: 25.05.2026
Accepted: 11.06.2026

In print: ISSN 2545-4447
On line: ISSN 2545-4455
doi:
Original research paper

SOIL ORGANIC CARBON AND NITROGEN DYNAMICS UNDER CARBON FARMING AND CONVENTIONAL MANAGEMENT IN BARLEY AND CHICKPEA SYSTEMS IN NORTH MACEDONIA

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Abstract

Soil organic carbon (SOC) represents a key indicator of soil health, fertility, and the capacity of agroecosystems to contribute to climate change mitigation through carbon sequestration. Within the framework of the CARBONICA project, this study evaluates SOC dynamics in barley (*Hordeum vulgare L.*) and chickpea (*Cicer arietinum L.*) cultivated under contrasting management systems, carbon farming (CF) and conventional practices, across representative pilot sites in North Macedonia.

Soil sampling was conducted from the 0-20 cm layer using a stratified composite approach that accounted for crop type and management regime. Soil organic carbon (SOC) content was determined using the validated Walkley–Black method, focusing on the biologically active organic carbon fraction, while total nitrogen (TN) was quantified using the Kjeldahl method. Experimental setups included four treatment variants: chickpea under CF (B2) and conventional management (B3), and barley under conventional (B4) and CF practices (B5).

The results revealed distinct temporal and management-dependent patterns in SOC dynamics. In barley systems, SOC declined during the monitoring period under conventional management, decreasing from 1.34% at the start-point to 0.89% at the end-point. In contrast, carbon-farming practices promoted a substantial increase in SOC, from 1.25% to 1.68%, indicating enhanced carbon sequestration potential. Similar trends were observed in chickpea systems, where SOC under CF increased from 1.18% to 1.57%, while conventional management resulted in a decline from 1.22% to 0.91%. Total nitrogen exhibited distinct crop- and management-dependent dynamics. In barley, TN decreased from 1.27 to 1.01 mg g^{-1} under conventional management but increased from 1.28 to 1.36 mg g^{-1} under carbon-farming practices. In contrast, chickpea showed progressive nitrogen enrichment throughout the growing season, reaching 1.41 and 1.45 mg g^{-1} under conventional and carbon-farming management, respectively.

The study provides region-specific evidence supporting the implementation of regenerative agricultural practices for improving soil quality, increasing carbon storage, and promoting sustainable land management in North Macedonia.

Key words: *soil organic carbon, nitrogen, carbon farming, barley, chickpea, sustainable agriculture, North Macedonia.*

INTRODUCTION

Soils constitute one of the most important natural resources supporting agricultural production, ecosystem functioning, and environmental sustainability (Bhaduri et al., 2022). Among the numerous indicators used to assess soil quality, soil organic carbon (SOC) is widely recognized as a key parameter reflecting soil fertility, biological activity, nutrient availability, structural stability, and long-term ecosystem resilience (Veum et al., 2014; Sofo et al., 2022; Sakin et al., 2024). As the largest terrestrial carbon reservoir, soils contain more carbon than the atmosphere and vegetation combined, making SOC a central component of both global biogeochemical cycles and climate-change mitigation strategies. Consequently, the preservation and enhancement of SOC stocks have become major priorities within international environmental policies, sustainable agricultural frameworks, and climate-neutral development agendas.

The growing concern regarding global climate change has intensified scientific interest in agricultural soils as potential carbon sinks capable of contributing to greenhouse-gas mitigation (Ekka et al., 2023). The agricultural sector is simultaneously affected by and contributes to climate change through greenhouse-gas emissions, soil degradation, biodiversity loss, and declining ecosystem services (Rehman et al., 2022; Pereira et al., 2025). In response, international initiatives such as the Paris Climate Agreement, the European Green Deal, the Farm-to-Fork Strategy, and the "4 per 1000" Initiative have emphasized the strategic importance of increasing carbon sequestration in agricultural soils. These policy frameworks recognize SOC not only as an indicator of soil quality but also as a measurable tool for improving climate resilience, enhancing agricultural sustainability, and supporting ecosystem restoration (Kamyab et al., 2024).

Despite its importance, SOC has been continuously declining in many agricultural regions worldwide due to intensive land-use practices. Conventional agricultural systems often rely on intensive tillage, simplified crop rotations, residue removal, excessive soil disturbance, and inadequate organic matter replenishment (Gebeyehu et al., 2017). Such practices accelerate the mineralization of soil organic matter, increase carbon losses through oxidation, reduce aggregate stability, and enhance susceptibility to erosion processes. Long-term depletion of SOC adversely affects soil productivity, water-retention capacity, nutrient cycling, microbial diversity, and overall ecosystem functioning. Recent studies indicate that the restoration of SOC stocks represents one of the most effective approaches for simultaneously improving agricultural productivity and environmental sustainability while strengthening the resilience of farming systems under increasingly variable climatic conditions (Chatterjee et al., 2020; Xiang et al., 2022; Han et al., 2023; Liu et al., 2023; Ma et al., 2023; Siddique et al., 2024; Alvyra et al., 2025; Huang et al., 2026).

Within this context, carbon farming has emerged as an innovative and science-based approach for integrating climate mitigation objectives into agricultural production systems (Sarmah & Bora, 2025). Carbon farming encompasses a range of management practices designed to increase carbon capture and storage in soils and biomass while maintaining economically viable agricultural production. Common carbon-farming measures include conservation tillage, reduced soil disturbance, residue retention, cover cropping, diversified crop rotations, optimized nutrient management, agroforestry systems, and practices aimed at enhancing soil biological activity (Loria & Lal, 2025). Numerous studies have demonstrated that these approaches can significantly improve soil carbon sequestration, soil structure, water-use efficiency, nutrient retention, and microbial biodiversity. Furthermore, carbon-farming systems have been associated with increased resilience to drought, reduced erosion risk, and improved long-term sustainability of agricultural landscapes (Sarmah & Bora, 2025).

The effectiveness of carbon-farming practices largely depends on local agroecological conditions, soil characteristics, climatic factors, and crop selection (Bayata & Mulatu, 2024). Different crop species contribute differently to SOC accumulation through variations in biomass production, root architecture, residue quality, rhizosphere interactions, and nutrient cycling processes. Consequently, crop-specific assessments are essential for understanding the mechanisms governing soil carbon dynamics under contrasting management systems (Piscitelli et al., 2023).

Barley (*Hordeum vulgare L.*) represents one of the most widely cultivated cereal crops in temperate and semi-arid agricultural regions. Due to its adaptability to diverse environmental conditions, relatively high biomass production, and extensive root system, barley has considerable potential to contribute to carbon inputs in agricultural soils. However, the extent of SOC accumulation in barley-based systems is strongly influenced by management practices, residue incorporation, and the degree of soil disturbance. Conservation-oriented management approaches have been reported to improve carbon retention and aggregate stabilization in cereal production systems, thereby enhancing both soil quality and crop productivity (Babaeian et al., 2023).

In contrast, chickpea (*Cicer arietinum L.*) is among the most important grain legumes cultivated under Mediterranean and semi-arid conditions. Leguminous crops play a particularly important role in sustainable agriculture due to their capacity for biological nitrogen fixation and their positive effects on soil fertility. Through symbiotic associations with nitrogen-fixing microorganisms, chickpea contributes to improved nutrient cycling, reduced dependency on synthetic fertilizers, enhanced microbial activity, and greater stabilization of soil organic matter. Previous studies have suggested that legume-based cropping systems may promote SOC accumulation through increased root-derived carbon inputs and stimulation of rhizosphere processes, particularly when combined with conservation agricultural practices (Rabbi et al., 2018; Chakrabarti et al., 2020;Lamichaney et al., 2021; Rahman et al., 2026).

The Western Balkan region, including North Macedonia, is increasingly exposed to the consequences of climate variability, land degradation, soil erosion, and declining soil organic matter levels. Many agricultural soils in the region are characterized by relatively low organic carbon content, particularly in intensively managed arable lands where prolonged cultivation and conventional management have accelerated organic matter depletion. Despite the growing international evidence supporting carbon-farming practices, scientific information regarding their effectiveness under the specific agroecological conditions of North Macedonia remains limited. The generation of locally relevant data is therefore essential for supporting evidence-based agricultural policies, climate-adaptation strategies, and sustainable land-management initiatives.

The CARBONICA project was established to address this knowledge gap by evaluating the implementation of carbon-farming practices under representative agricultural production systems in North Macedonia (Balabanova et al., 2025). Within this framework, the present study investigates the dynamics of soil organic carbon in barley and chickpea cultivated under carbon-farming and conventional management systems. Particular emphasis was placed on monitoring temporal changes in SOC throughout the vegetation period and evaluating the capacity of carbon-farming practices to enhance soil carbon accumulation under regional agroecological conditions (Neofytou et al., 2024; Kitsou et al., 2025).

The working hypothesis of this study was that carbon-farming management practices would promote greater SOC retention and accumulation compared to conventional agricultural practices, regardless of crop type, while crop-specific responses would reflect differences in biomass production, residue quality, and biological interactions within the soil environment. The results are expected to contribute to the scientific understanding of SOC dynamics in Southeastern European agroecosystems and provide practical evidence supporting the broader adoption of climate-smart and regenerative agricultural practices.

MATERIAL AND METHODS

Study area and experimental design

The present investigation was conducted within the framework of the CARBONICA project (Carbon Initiative for Climate-Resilient Agriculture), aiming to evaluate the effectiveness of carbon-farming practices in improving soil quality and enhancing soil organic carbon sequestration under representative agroecological conditions in North Macedonia. The field experiment was established at pilot agricultural plots managed under contrasting production systems, namely carbon farming (CF) and conventional agricultural management (CONV). Two economically important crop species were selected as model systems: barley (*Hordeum vulgare L.*) and chickpea (*Cicer arietinum L.*). Both crops represent important components of regional crop production systems and provide distinct biological characteristics influencing soil carbon dynamics. The experimental area was divided into four treatment variants: B2 – Chickpea under carbon-farming management; B3 – Chickpea under conventional management; B4 – Barley under conventional management; B5 – Barley under carbon-farming management.

Each experimental plot covered approximately 0.25 ha and was managed according to predefined agronomic protocols throughout the vegetation period. Conventional management followed standard regional agricultural practices, including mineral fertilization, conventional soil preparation, and routine crop management measures. Carbon-farming treatments incorporated regenerative agricultural practices designed to enhance soil carbon sequestration and improve soil health. These practices included reduced soil disturbance, increased residue retention, optimization of nutrient management, stimulation of biological activity, and the incorporation of plant biomass into the soil after harvest. The experiment was monitored throughout the entire vegetation cycle, allowing the assessment of temporal changes in soil organic carbon and associated agrochemical parameters under different management systems.

Soil sampling strategy

Soil sampling was conducted at pilot sites located in Amzabegovo, Sveti Nikole region, North Macedonia (41°48'46.87"N 21°59'56.57"E), characterized by a semi-arid continental climate with hot, dry summers and moderate annual precipitation. The experimental fields are situated on agricultural soils classified according to the World Reference Base (WRB) as Calcaric Cambisols, representative of the dominant soil resources in the Ovce Pole agricultural region. Soil samples were collected from the 0-20 cm layer at three critical stages of crop development: start-point (beginning of vegetation), mid-point (active vegetation stage), and end-point (post-harvest assessment).

Sampling was performed using a stratified composite approach that accounted for crop type and management regime. Within each experimental plot, multiple subsamples were collected from randomly selected points and combined into representative composite samples. SOC content was determined using the validated Walkley-Black method, focusing on the biologically active organic carbon fraction. Experimental setups included four treatment variants: chickpea under CF (B2) and conventional management (B3), and barley under conventional (B4) and CF practices (B5).

Agrochemical soil characterization

A comprehensive agrochemical characterization of soil samples was performed to evaluate the influence of crop type and management system on soil quality. Soil reaction was determined as pH(H_2O) and pH(KCl) using calibrated pH electrodes. Measurements were performed in soil suspensions prepared according to standard analytical procedures. Electrical conductivity (EC) was determined in aqueous soil extracts and expressed as mS/ cm, providing information regarding soluble salt content and general soil chemical status.

Total nitrogen (TN) content was determined using the Kjeldahl method. Soil samples were subjected to sulfuric acid digestion in the presence of catalytic reagents, followed by ammonia distillation and titrimetric quantification. Results were expressed as mg/g dry soil. Available phosphorus (P_2O_5) and potassium (K_2O) were determined using standard soil extraction procedures routinely applied in agrochemical laboratories. Quantification was performed using spectrophotometric and instrumental analytical techniques, respectively, and the results were expressed as mg/100 g soil.

The obtained agrochemical data were used to assess nutrient dynamics and evaluate the influence of carbon-farming practices on soil fertility throughout the experimental period.

Determination of soil organic carbon

The primary analytical parameter investigated in this study was soil organic carbon (SOC). SOC was determined using the validated Walkley–Black wet oxidation method, a widely accepted procedure for quantifying the biologically active fraction of soil organic carbon (Balabanova et al., 2024; Piperevski & Balabanova, 2026). The method is based on oxidation of organic matter by potassium dichromate ($K_2Cr_2O_7$) in the presence of concentrated sulfuric acid. Briefly, a known mass of finely ground soil was treated with a standardized potassium dichromate solution and concentrated sulfuric acid. Following the oxidation reaction, the excess dichromate was quantified by titration using a standardized ferrous ammonium sulfate solution. The amount of oxidized organic carbon was calculated stoichiometrically and expressed as a percentage SOC. The Walkley–Black procedure was selected due to its suitability for monitoring management-induced changes in soil organic carbon and its widespread application in agricultural and environmental studies (Piperevski & Balabanova, 2026).

Quality assurance and quality control

Quality assurance (QA) and quality control

(QC) procedures were implemented throughout all stages of sampling, sample preparation, and laboratory analysis to ensure the reliability, accuracy, and traceability of the generated data. All analytical activities were conducted at the UNILAB Research Laboratory, Faculty of Agriculture, Goce Delcev University, Stip, following standardized operating procedures developed in accordance with the principles of ISO/IEC 17025 for testing laboratories.

To minimize analytical uncertainty and ensure data integrity, laboratory quality control measures included the analysis of reagent blanks, duplicate sample preparation and measurement, calibration verification checks, and routine performance monitoring of analytical equipment. All reagents used were of analytical grade, while laboratory glassware and measuring devices were subjected to regular verification and maintenance procedures.

Particular attention was devoted to the determination of soil organic carbon using the Walkley-Black method. Method performance was continuously assessed through replicate analyses, evaluation of analytical precision, and verification of reagent stability. Quality assurance and quality control (QA/QC) procedures were implemented throughout the analytical process following the laboratory validation protocol described by Piperevski and Balabanova (2026). Method performance was evaluated through replicate analyses, recovery studies, and precision assessment. The validated Walkley-Black procedure demonstrated satisfactory repeatability, with relative standard deviation (RSD) values below 5% for replicate measurements. Recovery rates obtained from certified reference and spiked soil samples ranged between 95% and 105%, confirming the accuracy of the method. Duplicate sample analyses showed deviations lower than 5%, which was adopted as the acceptance criterion for analytical precision. Method blanks were routinely included to monitor potential contamination, and all analytical results fulfilled the established QA/QC acceptance criteria. These validation parameters confirmed the reliability and suitability of the method for monitoring soil organic carbon dynamics under field conditions (Piperevski & Balabanova, 2026).

Analytical traceability was ensured through documented laboratory procedures, controlled sample handling, standardized data recording, and systematic verification of analytical calculations. The generated results were evaluated with respect to precision, repeatability, and consistency prior to statistical processing. These quality assurance measures provided confidence in the reliability of the obtained soil organic carbon and agrochemical data and ensured their suitability for subsequent interpretation of management-induced changes under carbon-farming and conventional agricultural systems.

Data processing and statistical evaluation

Experimental data were processed using descriptive statistical methods. Temporal changes in soil organic carbon and agrochemical parameters were evaluated by comparing start-point, mid-point, and end-point measurements for each treatment variant. Relative changes (%) were calculated to assess the effectiveness of carbon-farming practices in comparison with conventional management systems. Particular emphasis was placed on evaluating management-dependent SOC dynamics in barley and chickpea systems and identifying trends associated with carbon sequestration, nutrient retention, and soil quality improvement. The obtained results were interpreted in relation to crop-specific characteristics, biological nitrogen fixation potential, residue management practices, and the broader objectives of climate-smart and regenerative agriculture.

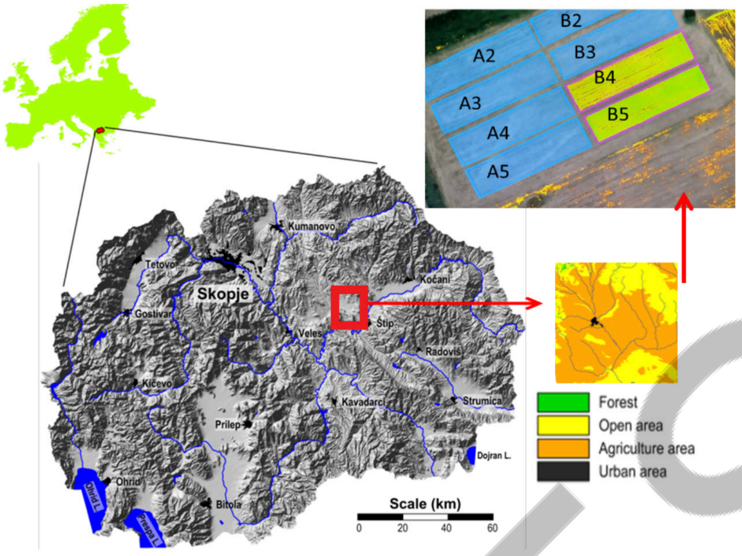

Figure 1. Field setup for the barley and chickpea experiments at the CARBONICA pilot site: B2 – Chickpea under carbon-farming management; B3 – Chickpea under conventional management; B4 – Barley under conventional management; B5 – Barley under carbon-farming management.

RESULTS AND DISCUSSION

Agrochemical soil characterization

The agrochemical characterization of soils under barley and chickpea cultivation revealed distinct temporal and management-dependent variations in soil fertility parameters throughout the experimental period (Table 1a and 1b). The monitored indicators, including soil reaction, electrical conductivity (EC), total nitrogen (TN), available phosphorus (P_2O_5), and available potassium (K_2O), provided valuable insight into the influence of carbon-farming and conventional management systems on soil quality and nutrient dynamics.

Across all experimental treatments, soil reaction remained within the alkaline range, with pH(H_2O) values generally varying between 8.1 and 8.7, reflecting the calcareous nature of the investigated soils. Although minor temporal fluctuations were observed, no substantial differences between management systems were detected. The relatively stable pH values indicate that neither conventional nor carbon farming practices induced significant alterations in soil acidity during the experimental period. Similar findings have been reported in conservation agriculture studies where short-term implementation of regenerative practices affected nutrient cycling more rapidly than soil reaction parameters.

Electrical conductivity values remained low throughout the study, indicating the absence of salinity-related constraints for crop development. The observed EC values ranged between 0.38 and 0.54 mS/cm, which are considered favorable for both barley and chickpea cultivation. The relatively stable EC values further suggest that the implemented management practices did not result in excessive accumulation of soluble salts within the root zone.

More pronounced differences were observed for nutrient-related parameters. Total nitrogen content exhibited clear crop-specific and management-dependent trends. In the barley production system, nitrogen concentrations remained relatively stable under carbon-farming management and showed an increase during the final assessment period, whereas conventional management was associated with a gradual decline. These results suggest improved nitrogen retention under carbon-farming conditions, likely resulting from enhanced biological activity, increased residue incorporation, and more efficient nutrient cycling processes.

The effect was even more evident in chickpea cultivation, where total nitrogen concentrations increased throughout the experimental period, particularly under carbon-farming management. The highest nitrogen values were recorded in the carbon-farming chickpea treatment at the end-point assessment. This response can be attributed to the leguminous nature of chickpea and its ability to establish symbiotic associations with nitrogen-fixing microorganisms. Enhanced biological nitrogen fixation, combined with improved soil biological functioning under regenerative management, likely contributed to the observed nitrogen accumulation.

Available phosphorus and potassium also demonstrated favorable trends under carbon-farming management. While some variability was observed among sampling periods, carbon-farming treatments generally maintained comparable or higher nutrient availability relative to conventional systems. The improved nutrient status may be associated with increased microbial activity, enhanced organic matter turnover, and improved nutrient retention mechanisms frequently reported in regenerative agricultural systems.

Table 1a. Agrochemical characteristics of soils under carbon-farming and conventional management systems during the experimental period - Barley cultivation system.

Parameter	Unit	CMS (Start-point)	CF (Start-point)	CMS (Mid-point)	CF (Mid-point)	CMS (End-point)	CF (End-point)
EC	mS/cm	0.48	0.50	0.49	0.38	0.49	0.43
pH (H_2O)	-	8.15	8.25	8.58	8.61	8.63	8.71
pH (KCl)	-	7.59	7.55	7.48	7.87	7.80	7.73
Available K_2O	mg/100 g	37.1	34.9	86.1	74.4	86.1	47.7
Available P_2O_5	mg/100 g	15.8	15.2	42.6	42.9	42.6	23.2
Total N	mg/g	1.27	1.28	1.01	1.04	1.01	1.36
Soil organic carbon (SOC)	%	1.34	1.25	1.08	1.45	0.89	1.68
Organic matter	%	9.69	8.53	1.75	1.66	1.75	1.57

*CF - Carbon Farming , CMS – Conventional management system, Values extracted from the CARBONICA agrochemical monitoring database.

Table 1b. Agrochemical characteristics of soils under carbon-farming and conventional management systems during the experimental period - Chickpea cultivation system.

Parameter	Unit	CMS (Start-point)	CF (Start-point)	CMS (Mid-point)	CF (Mid-point)	CMS (End-point)	CF (End-point)
EC	mS/cm	0.46	0.47	0.45	0.61	0.45	0.49
pH (H_2O)	-	8.49	8.45	8.59	8.52	8.27	8.13
pH (KCl)	-	7.56	7.57	7.83	7.79	7.30	7.27
Available K_2O	mg/100 g	42.5	32.7	92.5	106.9	84.9	84.9
Available P_2O_5	mg/100 g	36.5	33.16	46.6	44.8	42.8	43.7
Total N	mg/g	1.02	1.28	1.29	1.33	1.41	1.45
Soil organic carbon (SOC)	%	1.22	1.18	1.05	1.12	0.91	1.57
Organic matter	%	6.30	6.98	2.10	1.98	2.47	2.25

*CF - Carbon Farming , CMS – Conventional management system, Values extracted from the CARBONICA agrochemical monitoring database.

SOIL ORGANIC CARBON DYNAMICS UNDER CARBON FARMING AND CONVENTIONAL MANAGEMENT SYSTEMS

Soil organic carbon (SOC) is widely regarded as one of the most sensitive indicators of soil quality and the effectiveness of agricultural management practices. Changes in SOC content directly reflect the balance between carbon inputs originating from plant biomass and carbon losses resulting from decomposition, mineralization, erosion, and agricultural disturbance. Consequently, monitoring SOC dynamics provides valuable information regarding the capacity of agricultural systems to maintain soil fertility while simultaneously contributing to climate-change mitigation through carbon sequestration.

The present study revealed clear management-dependent differences in SOC dynamics for both investigated crops. Carbon-farming practices consistently promoted greater SOC retention and accumulation compared with conventional management, confirming the positive influence of regenerative agricultural practices on soil carbon storage under the agroecological conditions of North Macedonia.

The most pronounced response was observed in the barley production system. At the beginning of the experimental period, SOC values were relatively similar between the two management systems. However, temporal trends diverged substantially during the vegetation cycle. Under conventional management, SOC progressively decreased from 1.34% at the start-point to 1.08% during the mid-point assessment and further declined to 0.89% at the end-point assessment. This continuous reduction indicates a net loss of soil carbon, most likely associated with enhanced mineralization of organic matter and limited replenishment of carbon inputs.

In contrast, barley cultivated under carbon-farming management exhibited a completely different trajectory. SOC increased from 1.25% at the start-point to 1.45% during the mid-point assessment and reached 1.68% at the end-point of the experiment. Compared with the initial value, this represents an overall increase of approximately 34.4%, highlighting the strong capacity of carbon-farming practices to stimulate carbon accumulation and stabilization in cereal-based production systems.

The observed differences can be attributed to several mechanisms associated with regenerative management. Reduced soil disturbance minimizes aggregate disruption and decreases microbial exposure to previously protected organic matter. Simultaneously, residue retention increases the return of organic carbon to the soil, while improved biological activity promotes the formation of stable carbon pools. Similar findings have been reported in long-term studies investigating conservation agriculture and carbon-farming systems, where reduced tillage and increased biomass incorporation resulted in significant SOC accumulation and improved soil structural stability.

Chickpea exhibited a somewhat different but equally important response pattern. Under conventional management, SOC gradually declined throughout the vegetation period, decreasing from 1.22% at the beginning of the experiment to 1.05% during the mid-point assessment and finally reaching 0.91% at the end-point. Although the magnitude of decline was lower than that observed in barley, the results nevertheless indicate a progressive depletion of soil carbon reserves under conventional agricultural management.

In contrast, chickpea grown under carbon-farming conditions maintained relatively stable SOC levels during the active growth stage and showed a marked increase at the end of the experimental period. SOC changed from 1.18% at the start-point to 1.12% during the mid-point assessment and reached 1.57% at the end-point assessment, corresponding to an overall increase of approximately 33.1% relative to the initial condition.

The more moderate SOC response observed in chickpea during the mid-point assessment compared with barley is likely associated with crop-specific physiological characteristics. As a leguminous species, chickpea contributes substantially to below-ground carbon inputs through root exudation and root biomass production. Furthermore, biological nitrogen fixation improves nitrogen availability within the rhizosphere, stimulating microbial activity and promoting the formation of stable soil organic matter. These processes may enhance SOC stabilization even when above-ground biomass production is lower than in cereal-based systems.

A direct comparison between crops indicates that both species benefited from carbon-farming management; however, barley demonstrated a slightly greater final SOC accumulation (1.68%) compared with chickpea (1.57%). This finding suggests that cereal-based carbon-farming systems may offer particularly high potential for carbon sequestration under the climatic and edaphic conditions characteristic of North Macedonia. Nevertheless, the positive response observed in chickpea highlights the complementary role of legumes in regenerative cropping systems, where biological nitrogen fixation and improved nutrient cycling contribute to long-term soil quality enhancement.

Overall, the results clearly demonstrate that carbon-farming practices effectively reversed the declining SOC trends observed under conventional management. The sustained increase in SOC recorded in both barley and chickpea confirms the potential of regenerative agricultural practices to improve soil carbon stocks, strengthen soil health, and contribute to climate-smart agricultural development. These findings support current European initiatives promoting carbon farming as a practical mechanism for increasing carbon sequestration in agricultural soils while simultaneously improving agroecosystem sustainability and resilience.

Table 2. Temporal changes in soil organic carbon (SOC) and total nitrogen (TN) under conventional (CMS) and carbon-farming (CF) management systems in barley and chickpea cultivation.

Crop	Start-point	Mid-point	End-point	Relative change (%)
Barley CMS	SOC = 1.34% TN = 1.27 mg g^{-1}	SOC = 1.08% TN = 1.01 mg g^{-1}	SOC = 0.89% TN = 1.01 mg g^{-1}	SOC: −33.6 TN: -20.5
Barley CF	SOC = 1.25% TN = 1.28 mg g^{-1}	SOC = 1.45% TN = 1.04 mg g^{-1}	SOC = 1.68% TN = 1.36 mg g^{-1}	SOC: +34.4 TN: +6.3
Chickpea CMS	SOC = 1.22% TN = 1.02 mg g^{-1}	SOC = 1.05% TN = 1.29 mg g^{-1}	SOC = 0.91% TN = 1.41 mg g^{-1}	SOC: −25.4 TN: +38.2
Chickpea CF	SOC = 1.18% TN = 1.28 mg g^{-1}	SOC = 1.12% TN = 1.33 mg g^{-1}	SOC = 1.57% TN = 1.45 mg g^{-1}	SOC: +33.1 TN: +13.3

*CF - Carbon Farming , CMS – Conventional management system, SOC – Soil organic carbon, TN - Total nitrogen, Values extracted from the CARBONICA agrochemical monitoring database.

NITROGEN DYNAMICS AND CROP-SPECIFIC RESPONSES

Total nitrogen (TN) dynamics demonstrated pronounced crop-specific and management-dependent responses throughout the experimental period (Table 2). Nitrogen availability is closely associated with soil fertility, microbial activity, organic matter turnover, and long-term soil carbon stabilization. Consequently, the observed TN trends provide important insight into the functioning of carbon-farming systems and their influence on nutrient cycling processes.

In the barley production system, contrasting TN dynamics were observed between conventional and carbon-farming management. Under conventional management, TN concentrations declined from 1.27 mg g^{-1} at the start-point to 1.01 mg g^{-1} during the mid-point assessment and remained at 1.01 mg g^{-1} at the end-point. This trend indicates a reduction in available nitrogen reserves and suggests that nutrient removal through crop uptake exceeded the replenishment capacity of the soil system.

Conversely, barley cultivated under carbon-farming management exhibited improved nitrogen retention. Although TN decreased slightly from 1.28 mg g^{-1} at the start-point to 1.04 mg g^{-1} during the mid-point assessment, a substantial increase was observed at the end-point, reaching 1.36 mg g^{-1}. Compared with the initial concentration, this corresponds to an overall increase of approximately 6.3%, indicating more efficient nutrient conservation and recycling under regenerative management conditions.

The nitrogen response was also evident in the chickpea production system. Under conventional management, TN increased steadily from 1.02 mg g^{-1} at the start-point to 1.29 mg g^{-1} during the mid-point assessment and reached 1.41 mg g^{-1} at the end-point. This represents an overall increase of approximately 38.2%, demonstrating the capacity of chickpea cultivation to enrich soil nitrogen even under conventional management.

Under carbon-farming conditions, chickpea showed a similar but slightly stronger response. TN increased from 1.28 mg g^{-1} at the beginning of the experiment to 1.33 mg g^{-1} during the active vegetation stage and reached 1.45 mg g^{-1} at the end-point assessment. This corresponds to an overall increase of approximately 13.3% relative to the initial value. Although the increase was less pronounced than previously estimated, the treatment maintained the highest final TN concentration among the chickpea treatments while simultaneously supporting greater SOC accumulation.

The observed increase in TN under chickpea cultivation is closely associated with biological nitrogen fixation. Through symbiotic associations with Rhizobium spp., chickpea is capable of converting atmospheric nitrogen into plant-available forms, thereby increasing nitrogen availability within the rhizosphere and contributing to soil fertility improvement. The positive TN response observed under carbon-farming management suggests that regenerative practices created favorable conditions for biological nitrogen fixation, microbial activity, and nutrient conservation.

These findings are consistent with previous studies reporting enhanced nitrogen retention under conservation and regenerative agricultural systems. Bohoussou et al. (2026) demonstrated that conservation agriculture practices significantly improved both soil organic carbon and total nitrogen storage compared with conventional tillage systems. Similarly, Bragg et al. (2025) reported increased TN accumulation under reduced tillage and organic management systems due to improved microbial functioning and enhanced nutrient cycling processes.

The crop-specific responses observed in the present study further emphasize the complementary ecological roles of cereals and legumes within carbon-farming systems. While barley demonstrated the strongest response in terms of soil organic carbon accumulation, chickpea exhibited a greater capacity for biological nitrogen enrichment. Such complementarity is particularly important for regenerative agriculture, where diversified crop systems aim to simultaneously improve nutrient cycling, carbon sequestration, soil fertility, and overall agroecosystem resilience.

The nitrogen dynamics observed in this study also provide a mechanistic explanation for the SOC trends discussed in the subsequent section. Increased nitrogen availability promotes plant biomass production, root development, and microbial growth, all of which contribute additional carbon inputs to the soil. Consequently, the enhanced TN accumulation recorded under carbon-farming management likely played an important role in supporting the greater SOC stabilization and sequestration observed in both barley and chickpea systems.

The calculated C ratios provided additional insight into the balance between soil organic carbon accumulation and nitrogen dynamics under the investigated management systems (Figure 2). In barley, carbon-farming management maintained more favorable carbon-to-nitrogen relationships compared with conventional management. The C:N ratio under barley carbon farming increased from 9.77 at the start-point to 13.94 at the mid-point and stabilized at 12.3 at the end-point, indicating enhanced carbon accumulation while maintaining adequate nitrogen availability. In contrast, conventional barley showed a decline from 10.5 at the start-point to 8.81 at the end-point, suggesting reduced carbon retention and more intensive organic matter mineralization.

In chickpea systems, contrasting trends were observed. Under conventional management, the C ratio declined from 11.9 at the start-point to 8.14 at the mid-point and further to 6.45 at the end-point. Under carbon-farming management, the ratio decreased from 9.22 at the start-point to 8.42 at the mid-point but remained substantially higher at the end-point (10.8) compared with conventional management. This finding indicates that carbon-farming practices supported simultaneous SOC accumulation and nitrogen retention, resulting in a more balanced carbon-to-nitrogen relationship. The higher final C ratio observed under carbon-farming chickpea reflects enhanced carbon sequestration efficiency rather than nitrogen limitation and further supports the positive influence of regenerative management on soil quality and nutrient cycling.

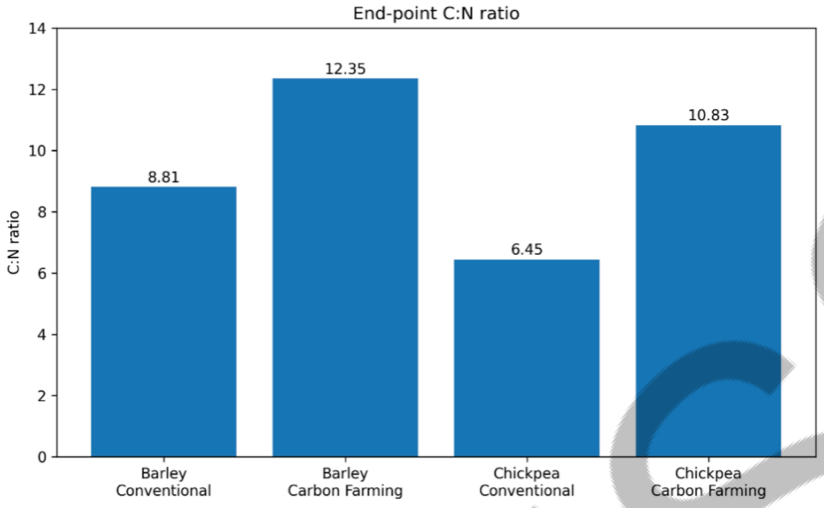

Figure 2. End-point C:N ratio under carbon-farming and conventional management systems in barley and chickpea cultivation.

CONCLUDING REMARKS

The present study provides region-specific evidence on the effectiveness of carbon-farming practices for improving soil quality and enhancing soil organic carbon (SOC) accumulation under representative agroecological conditions in North Macedonia. The results clearly demonstrated that management practices significantly influenced both carbon and nitrogen dynamics, with carbon-farming systems consistently outperforming conventional agricultural management.

Among the investigated crops, barley exhibited the strongest response in terms of SOC sequestration. Under carbon-farming management, SOC increased from 1.25% at the start-point to 1.68% at the end-point, corresponding to an increase of approximately 34.4%. In contrast, conventional management resulted in a continuous decline from 1.34% to 0.89%, indicating substantial carbon depletion. These findings confirm the strong potential of cereal-based carbon-farming systems to contribute to long-term carbon storage, improved soil quality, and enhanced climate-change mitigation.

Chickpea displayed a different but equally important response pattern. Carbon-farming management increased SOC from 1.18% to 1.57%, representing an overall increase of approximately 33.1%, whereas conventional management resulted in a decline from 1.22% to 0.91%. In addition, chickpea promoted substantial nitrogen enrichment, with total nitrogen increasing from 1.28 to 1.45 mg g^{-1} under carbon-farming conditions and from 1.02 to 1.41 mg g^{-1} under conventional management. These responses highlight the important role of biological nitrogen fixation and legume-based systems in supporting nutrient cycling, nitrogen availability, and soil fertility.

The calculated C ratios further emphasized the complementary functions of the two crops within regenerative agricultural systems. Barley under carbon-farming management maintained the highest final C ratio (12.3), reflecting efficient carbon accumulation and stabilization. In contrast, chickpea exhibited lower C ratios due to enhanced nitrogen availability associated with biological nitrogen fixation. Together, these responses demonstrate the complementary ecological functions of cereals and legumes in regenerative cropping systems, where carbon sequestration and nutrient enrichment occur simultaneously.

The findings demonstrate that carbon-farming practices based on reduced soil disturbance, residue retention, and enhanced biological activity can effectively improve soil health, promote carbon sequestration, and increase the resilience of agricultural systems. The simultaneous enhancement of SOC and maintenance of favorable nitrogen dynamics under carbon-farming management highlights the potential of these practices to support sustainable crop production and climate-smart agriculture.

ACKNOWLEDGEMENT

The authors express their acknowledgment to the CARBONICA project, officially titled "Carbon Initiative for Climate-resilient Agriculture". The present research has been conducted in the framework of the CARBONICA project that has received funding from the Horizon Europe programme under Grant Agreement No. 101087233.

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ДИНАМИКА НА ОРГАНСКИОТ ЈАГЛЕРОД И АЗОТ ВО ПОЧВАТА ПОД ВЛИЈАНИЕ НА ЈАГЛЕРОДНО ЗЕМЈОДЕЛСТВО: СПОРЕДБЕНА СТУДИЈА КАЈ ЈАЧМЕН И НАУТ ВО СЕВЕРНА МАКЕДОНИЈА

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Резиме

Органскиот јаглерод во почвата (SOC) претставува клучен индикатор за здравјето и плодноста на почвата, како и за способноста на агроекосистемите да придонесат кон ублажување на климатските промени преку секвестрација на јаглерод. Во рамките на проектот CARBONICA, ова истражување ја оценува динамиката на органскиот јаглерод во почвата кај јачмен (Hordeum vulgare L.) и наут (Cicer arietinum L.) одгледувани под два различни системи на управување и тоа, јаглеродно земјоделство и конвенционално производство на репрезентативни пилот локации во Република Северна Македонија.

Земањето почвени примероци беше спроведено од слојот 0–20 cm со примена на стратифициран композитен пристап кој ги земаше предвид видот на културата и системот на управување. Содржината на SOC беше определена со валидираната метода на Walkley–Black, со фокус на биолошки активната фракција на органскиот јаглерод. Експерименталниот дизајн опфати четири варијанти: наут под јаглеродно земјоделство (B2) и конвенционално управување (B3), како и јачмен под конвенционално (B4) и јаглеродно земјоделство (B5).

Резултатите покажаа јасно изразени временски и управувачки зависни модели во динамиката на SOC. Кај системите со јачмен, содржината на јаглерод се намалуваше во текот на периодот на мониторинг под конвенционално управување, опаѓајќи од 1,34 % на почетната точка до 0,89 % на крајната точка. Наспроти тоа, практиките на јаглеродно земјоделство доведоа до значително зголемување на SOC, од 1,25 % на 1,68 %, што укажува на зголемен потенцијал за секвестрација на јаглерод. Слични трендови беа забележани и кај системите со наут, каде што содржината на јаглерод под јаглеродно земјоделство се зголеми од 1,18 % на 1,57 %, додека конвенционалното управување резултираше со намалување од 1,22 % на 0,91 %. Овие резултати ги нагласуваат позитивните ефекти од намаленото нарушување на почвата, задржувањето на растителните остатоци и зголемената биолошка активност поврзани со практиките на јаглеродно земјоделство. Дополнително, вклучувањето на легуминозни култури придонесе за подобрена стабилизација на јаглеродот преку биолошка фиксација на азот и стимулирање на микробиолошките процеси во почвата.

Практиките на јаглеродно земјоделство покажаа конзистентна способност за одржување и зголемување на нивото на органскиот јаглерод во споредба со конвенционалното управување, што ја потврдува нивната важност како климатски паметни земјоделски стратегии. Истражувањето обезбедува регионално специфични бази на податоци коишто ја поддржуваат примената на јаглеродни земјоделски практики со цел подобрување на квалитетот на почвата, зголемување на складирањето на јаглерод и промовирање на одрживо управување со земјиштето во Република Северна Македонија.

Клучни зборови: *органски јаглерод, јаглеродно земјоделство, секвестрација на јаглерод, наут, јачмен, Северна Македонија.*