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QUANTIFYING SOIL CARBON DYNAMICS: A COMPARATIVE ASSESSMENT OF CARBON FARMING VS. CONVENTIONAL SYSTEMS IN CORN AND SUNFLOWER CULTIVATION IN NORTH MACEDONIA

Biljana Balabanova[a*], Verica Ilieva[a], Blagoja Mukanov[b], Mario Petkovski[b], Jovana Milosavljeva[b], Ivan Donev[a] Kristina Panev[a], Natasa Mavromihailova[a]
[a]Faculty of agriculture, Goce Delcev University, Stip, North Macedonia / [b]AgFutura Technologies, Skopje, Republic of North Macedonia / corresponding e-mail: biljana.balabanova@ugd.edu.mk

GENERAL INTRODUCTION: Precise carbon determination transforms carbon farming from an empirical concept into a scientifically-driven, economically viable, and policy-relevant practice. It enables farmers and researchers to quantify soil health improvements and climate benefits, unlock new revenue via carbon markets, and foster adaptive management and sound policymaking rooted in hard data. In doing so, it advances the broader goal of sustainable, climate-smart agriculture—anchoring the study's comparative findings in real-world impact and long-term viability.

This study presents a comparative evaluation of carbon farming and conventional agricultural systems in the cultivation of corn (*Zea mays L.*) and sunflower (*Helianthus annuus L.*), focusing on their effects on soil carbon, nitrogen dynamics and other soil characteristics over a two-year period (2024-2025). Soil samples were collected at the beginning, midpoint, and end of the study to assess total organic carbon (TOC) and total nitrogen (TN) under each management system.

METHODOLOGY: Soil samples were collected from the **Ovce Pole region, eastern part of the territory of North Macedonia), including the landfill with the carbon farming practice (pilot site) as well.** The method validation was improved with QA protocol in accordance with the ISO/IEC 17025:2017. Accuracy, precision, LOD, LOQ, reproducitvity, reputability, measurement uncertainty and working range were included for the quality insurance of the method. The data normalization has been introduced using log-normal transformation, for excluding the outliers. Data matrix has been improved with bivariate statistics of correlation matrix and multivariate extraction of dominant variables.

Agro-chemical 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 carbon 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.

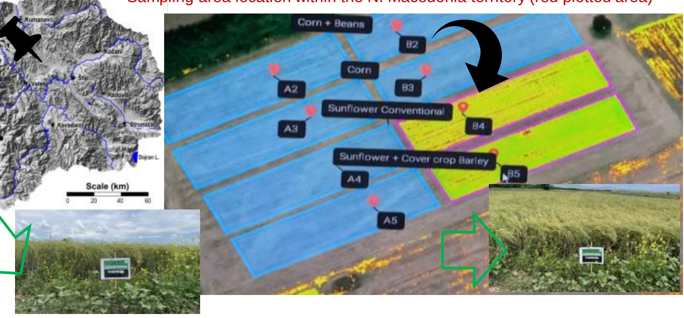
Total nitrogen (N) content in the soil was determined by the Kjeldahl method. This procedure includes the digestion of the soil sample with concentrated sulfuric acid in the presence of a catalyst to convert organic nitrogen into ammonium. The digest was then subjected to alkaline distillation, and the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

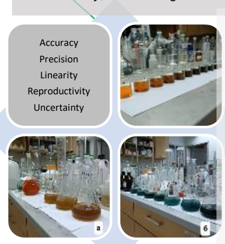
Exchangeable potassium (K) was extracted from the soil using 1M ammonium acetate solution. The potassium content in the extract was then quantified using either flame photometry or atomic absorption spectrophotometry (AAS), depending on the available instrumentation.

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.

Sampling area location within the N. Macedonia territory (red plotted area)



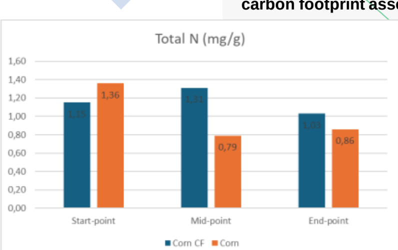
In 2024, a series of field activities were undertaken to assess the effectiveness of different agricultural practices on soil health and carbon sequestration. The experimental setups included corn and sunflower crops. The field for each crop was divided into two sub-plots (0.25 hectares for conventional production and 0.25 hectares for carbon farming). Conventional corn production involved sowing corn as a pure 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 pure 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.

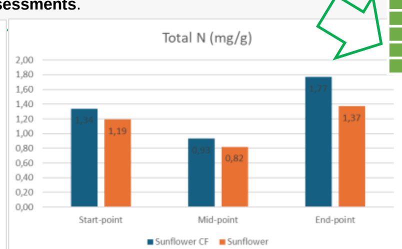


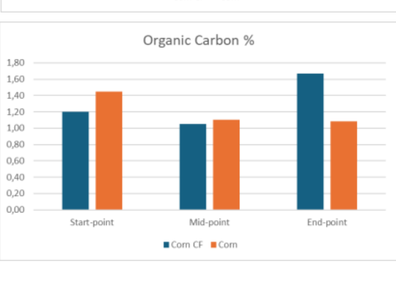
RESULTS AND DISCUSSION

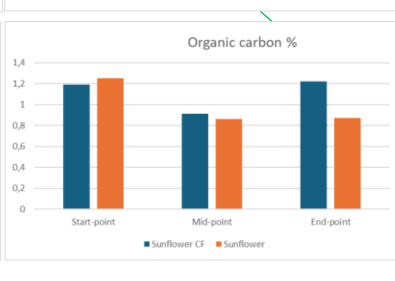
Climate variables such as temperature and precipitation significantly affect SOC dynamics. Warmer temperatures accelerate organic matter decomposition, potentially reducing SOC levels, while increased precipitation can enhance plant growth and organic matter input, promoting SOC accumulation. These climatic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

Start-point	$pH_{(KCl)}$	$pH_{(H2O)}$	EC (mS/cm)	Total N mg/g	P_2O_5 (mg/100g)	K_2O (mg/100g)	SOM (%)
A1	7.48	8.29	0.51	1.36	41.3	73.0	7.14
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)	P_2O_5 (mg/100g)	K_2O (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)	P_2O_5 (mg/100g)	K_2O (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









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 results are consistent with broader literature emphasizing the role of organic carbon as a cornerstone of 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.

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