

# From soil carbon towards system sustainability: Integrating SOC modelling and life cycle assessment to evaluate environmental trade-offs in carbon farming

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## ABSTRACT

The European Union (EU) is committed to reducing greenhouse gas (GHG) emissions to the atmosphere and promoting sustainable soil and land management practices. Carbon Farming (CF) is a set of practices to mitigate climate change in agriculture through carbon sequestration in soils. While CF practices increase soil organic carbon (SOC) stocks, they are also expected to have environmental impacts and potential trade-offs. However, the environmental impact of CF practices is often overlooked, and a comprehensive evaluation using Life Cycle Assessment (LCA) methodology is required. The RothC model was used to simulate SOC dynamics under different CF practices on arable land in Northern Italy: reduced tillage (RT), farmyard manure (FYM) application, and cover crops (CC). LCA methodology was applied to quantify GHG emissions and other environmental impacts beyond carbon. The results confirmed that different soil management strategies can significantly affect SOC accumulation. FYM application sequesters the most carbon (4.89 t C ha<sup>-1</sup> over 20 years) due to exogenous carbon inputs. RT (1.34 t C ha<sup>-1</sup>) and CC (1.73 t C ha<sup>-1</sup>) also contribute to sequestration, but at lower rates. However, LCA results revealed significant trade-offs: while FYM maximizes carbon sequestration (0.90 t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>), it substantially increases acidification (+254 %), marine eutrophication (+372 %), terrestrial eutrophication (+243 %), and photochemical ozone formation (+290 %) compared to conventional agriculture. In contrast, CC and RT provide a balanced profile with moderate sequestration benefits (0.32 and 0.25 t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>, respectively) and reduced environmental impacts, with RT showing improvements across all acidification and eutrophication indicators. This research underlines the critical need for comprehensive system assessment of agricultural sustainability, as CF may place too much emphasis on carbon sequestration without fully considering other environmental impacts requiring mitigation.

## 1. Introduction

The growing need to mitigate climate change has intensified efforts across all productive sectors, with agriculture receiving particular attention for its potential role in soil carbon sequestration (Nazir et al., 2024). Carbon sequestration in soils refers to the long-term storage of carbon in soil organic carbon (SOC) pools, helping to lower atmospheric concentrations of greenhouse gases (GHG) and support sustainable land management techniques (Lal, 2015). Because of its positive role in carbon sequestration, agriculture has a significant mitigation potential.

In the European Union (EU), the land use, land-use change, and forestry (LULUCF) sector reported negative values (−7 % in CO<sub>2</sub>-eq) (EEA, 2022). In this context, carbon farming (CF) is a promising strategy, as it involves practices primarily aimed at carbon sequestration, which is often measured in terms of SOC gains and greenhouse gas (GHG) balances (Pettersson et al., 2025), as well as improving soil health and biodiversity (Khangura et al., 2023). Carbon farming refers to agricultural practices that increase the sequestration and storage of carbon in soils and biomass, while reducing soil-related GHG emissions; it partially overlaps with regenerative agriculture, in terms of

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management practices, but is distinguished by its explicit and quantified focus on carbon removal. Unlike conventional farming, which tends to lead to soil degradation and GHG emissions, CF practices aim to restore soil systems and increase SOC stocks by using cover cropping, improved crop rotations, agroforestry, no-till and reduced tillage farming, organic farming and livestock integration (Schreefel et al., 2020). These practices not only sequester carbon but improve soil fertility and water retention capacity, and increase resilience to climate stress, in line with several Sustainable Development Goals (SDGs), such as zero hunger, climate action, and life on land (Lal et al., 2018; Bouma et al., 2019).

Despite evidence of the potential benefits under different soil management systems, actual carbon sequestration remains limited or inconsistent because of the barriers to the adoption of CF practices, especially in the Mediterranean region. Key barriers include limited economic incentives and high initial costs, lack of access to specialized equipment and technical knowledge, ineffective information dissemination in rural areas, and misalignment with traditional farming practices, fostering skepticism among farmers (Gonzales-Gemio and Sanz-Martín, 2025). Nevertheless, there is a significant opportunity to improve soil health by increasing the adoption of appropriate management practices (Heller et al., 2024).

Research into carbon sequestration in agricultural soils is steadily increasing, mainly due to the climate mitigation potential of CF practices (Arellano Vazquez et al., 2024). These practices show promising SOC gains and potential GHG mitigation. However, robust computational methods and techniques are needed to accurately determine the carbon sequestration potential of CF practices and their eventual environmental trade-offs. Existing studies typically focus on either carbon sequestration potential (Li et al., 2025) or the environmental impacts of agricultural practices, paying particular attention to Global Warming Potential (GWP) (Shi et al., 2026). While some studies have coupled carbon sequestration potential with Life Cycle Assessment (LCA), these are mostly limited to climate indicators (e.g. GWP) and do not explore a broader set of impact categories or environmental trade-offs (Goglio et al., 2014; Fantin et al., 2022). Currently, integrated assessments that couple process-based SOC modelling with LCA are lacking. In particular, few studies have combined process-based SOC modelling and LCA across multiple impact categories for CF practices in Mediterranean arable systems.

This study contributes to understanding the implementation of CF practices by combining a process-based soil model with LCA to quantify SOC dynamics, carbon sequestration and multi-impact environmental trade-offs. Soil models such as the RothC model (Coleman and Jenkinson, 1996) can simulate various land use and management scenarios using a small number of input parameters (Spotorno et al., 2024). LCA, on the other hand, is a systematic approach to evaluating the environmental benefits and costs of alternative farming methods to those traditionally used (Finnveden et al., 2009).

The novelty of this research lies in its evaluation of the broader environmental impacts of CF, extending beyond carbon sequestration. Integrating the RothC model with the LCA methodology enables a more comprehensive evaluation, ensuring that methods which encourage carbon sequestration do not inadvertently lead to increased environmental impacts in other areas (Brandão et al., 2013).

For the purpose of this study, the selected practices consist of implementing cover crops, transitioning from mineral/synthetic fertilization to organic fertilization and reducing tillage intensity. The main objectives of this study are to (i) estimate the carbon sequestration potential of the selected CF practices, (ii) compare their environmental impacts using LCA methodology, and (iii) identify optimal and sustainable strategies for increasing SOC sequestration while mitigating climate change. The final aim is to evaluate the carbon balance (CB) of a conventional three-year crop rotation in northern Italy, with and without CF practices. The CB is calculated as the difference between the GHG emissions associated with the agricultural phase of crop production and changes in SOC stock.

This study provides information on the environmental impact of crop production and helps assess management strategies that can improve agricultural sustainability. The findings are also relevant to the EU Carbon Removal Certification Framework (CRCF), which seeks to establish a reliable mechanism for monitoring, reporting, and certifying carbon removals. This research contributes to the development of science-based criteria for certifying soil-based carbon removals that are aligned with the EU's climate and sustainability goals by providing robust data on SOC dynamics and their environmental impacts. By identifying CF practices that optimize carbon sequestration while minimizing environmental trade-offs, this research contributes to a better definition of Voluntary Carbon Markets (Kochhar et al., 2025) and supports the transition towards sustainable agricultural systems.

## 2. Materials & methods

### 2.1. Study area and scenario definition

The study was conducted on a subset of twenty farms from the HelpSoil project, a demonstration project in the Po Valley (Italy) that implemented conservation agriculture on 20 farms over three cropping seasons to assess agronomic, environmental, and economic effects versus conventional systems (Perego et al., 2019). Primary management and input data (tillage intensity, fertilization rates, crop yields, machinery use) were collected from the HelpSoil project farm surveys and field records to ensure site-specific representation of the Po Valley region. Four of the twenty farms from the HelpSoil project were excluded from this study because they were not suitable for the purpose (e.g. due to rice cultivation – waterlogged conditions), or because these farms lacked key information to perform the SOC modelling and LCA. The assessment focused on a three-year crop rotation (maize – soya – wheat) and compared conventional systems with CF practices.

Four main scenarios (Table 1) were defined to evaluate SOC dynamics and associated greenhouse gas (GHG) emissions: Business-As-Usual (BAU), Cover Crops (CC), Reduced Tillage (RT) and the transition from inorganic fertilizers to organic fertilizers – FarmYard manure (FYM).

The BAU scenario reflects the conventional agriculture methods used in the Po Valley, which include heavy tillage, a reliance on mineral fertilizers, and a lack of cover crops. Crop residues are the main source of carbon input. This situation served as the baseline against which CF practices were evaluated. The CC scenario assumes the introduction of cover crops between cash crop cycles, thereby increasing annual carbon inputs to the soil and modifying soil cover. However, additional field operations increased diesel consumption, e.g. sowing, mowing, and biomass incorporation, and contributed to indirect emissions. Other inputs (e.g., pesticides, fertilizers) remain unchanged from the BAU scenario. The RT scenario models the adoption of reduced tillage

**Table 1**  
Scenarios description.

Scenario	Description
BAU (Business-As-Usual)	Conventional Po Valley system with heavy tillage, mineral fertilizers, and no cover crops. Crop residues are the sole carbon input, serving as the baseline for comparison.
CC (Cover Crops)	Introduction of cover crops between main crops to increase soil carbon input and cover. Involves extra field operations but reduces nutrient losses and irrigation needs while improving soil structure.
RT (Reduced Tillage)	Reduction of soil disturbance to slow organic matter decomposition and enhance SOC retention. Incorporates lower fuel use but possible yield penalties during transition years.
FYM (Farmyard Manure)	Partial replacement of mineral fertilizers with manure to increase organic carbon inputs. Includes emissions from manure handling and application, with nutrient balance maintained.

practices, which reduce soil disturbance and slow the decomposition of organic matter. Scenario emissions include reduced diesel consumption, with all other inputs remaining constant. In line with empirical evidence, the RT scenario was also associated with yield penalties (see Section 2.2 for details), which were included to reflect realistic agronomic trade-offs. In the FYM scenario, mineral fertilizers were reduced by 60 % and replaced with farmyard manure to maintain N-P-K nutrient balance and increase exogenous carbon inputs. To maintain stable N-P-K levels, mineral fertilizers were proportionately reduced, while emissions from FYM application (machinery use, direct emissions to air and water) were included.

## 2.2. RothC model parametrization

RothC-26.3 is a process-based model for simulating organic carbon dynamics in non-waterlogged topsoils. The model simulates changes in five distinct organic carbon pools and total SOC. The inputs required include soil texture, carbon inputs, climate data, vegetation cover, and the decomposability of incoming plant material. The five organic carbon pools modeled are decomposable plant material (DPM), resistant plant material (RPM), microbial mass (BIO), humified organic matter (HUM), and inert organic matter (IOM) (Jenkinson et al., 1987, 1991, 1992, 1997; Jenkinson and Coleman, 1994). A critical parameter in the model is the DPM/RPM ratio, typically set at 1.44 for most agricultural crops, indicating that plant material is composed of 59 % DPM and 41 % RPM. Decomposition rates for DPM, RPM, BIO, and HUM are influenced by climate, clay content, and vegetation cover. The model operates in two modes: an inverse mode, which calculates the annual carbon input required to achieve a specified equilibrium SOC content, and a forward mode, which simulates SOC dynamics based on predefined monthly carbon inputs.

RothC-26.3 was implemented using R version 4.0.3, specifically within the SoilR package (R Core Team, 2023). The default SoilR model was modified to include the effects of soil cover by adjusting the moisture function with a “vegetation cover factor”, which was derived from rescaled NDVI values, where 0 represents bare soil and 1 represents fully vegetated soil. A threshold of 0.8 was established to determine full vegetation cover. RothC-26.3 provides a robust framework for simulating soil organic carbon dynamics, incorporating key environmental and biological factors, and its adaptability is enhanced through the modification of the SoilR package to include soil cover effects. The model was first applied in inverse mode over a 10,000-year reference period to estimate the annual carbon inputs needed to achieve initial SOC levels, assuming that SOC was in equilibrium (“spin-up phase”). CF practices were then modeled by parameterising the RothC model.

The first scenario analyses the adoption of reduced tillage practices, such as no-tillage or reduced tillage, which decreases the decomposition rates of crop residues and thereby increases soil carbon stocks. Tillage Rate Modifier (TRM) factors were used to simulate the adoption of no-till and reduced tillage practices. These modifiers adjust the decomposition rate constants that control how carbon moves between soil carbon pools. In the RothC model, SOC is divided into different pools that represent different levels of decomposition. The decomposition of these pools over time was modeled by applying a set of rate modifiers. The equation used to describe this process is structured to account for several factors influencing decomposition, including temperature, moisture, and soil cover, represented by specific rate modifiers – Eq. (1).

$$SOC_{t+1} = SOC_t \times e^{-abcdkt} \quad (\text{Eq. 1})$$

Where  $SOC_t$  represents SOC ( $t \text{ C ha}^{-1}$ ) at time  $t$  and  $SOC_{t+1}$  represents SOC ( $t \text{ C ha}^{-1}$ ) at time  $t + 1$ . The  $k$  factor is constant and differs according to the specific compartment annual decomposition rate: 0.02 for HUM pool, 0.66 for BIO pool, 0.3 for RPM pool and 10 for DPM pool. The exponents are the rate modifiers:  $a$  for temperature,  $b$  for moisture, and  $c$  for soil cover. All exponents are unitless (Coleman and Jenkinson,

1996). In this equation the factor  $d$  is the TRM. Research showed that no-till practices correspond to a TRM of 0.95, while reduced tillage has a TRM of 0.93, relative to conventional high-intensity tillage with a default TRM of 1 (Jordon and Smith, 2022). The TRM factors are used to model the specific response to tillage practices. For instance, no-till or reduced tillage practices reduce the decomposition rate by reducing soil disturbance, and this effect is incorporated into the TRMs. As a result, the TRMs modify the rate at which carbon is cycled through each SOC compartment, allowing more precise simulation of soil carbon changes as tillage intensity is reduced (Hyun and Yoo, 2024). Empirical data on the impacts on yields of conservative tillage systems was included to capture agronomic trade-offs. According to previous studies (Pittelkow et al., 2015) the average yield reduction across 50 crops was 5.1 %, with crop-specific reductions of  $-2.6$  % for wheat, and  $-7.6$  % for maize. These patterns are supported by more recent analyses, which show reductions of between 6 % and 20 % during the initial transition years (van Balen et al., 2023; Yue et al., 2023). However, as soils adapt and crop rotations improve, these effects, which depend on the environmental context, may diminish over time.

The main factor contributing to the change in SOC following the adoption of CC is the increased carbon input they provide, while other minor effects are typically not considered (Bolinder et al., 2020). To account for this, the carbon inputs have been adjusted to reflect the additional organic matter from the cultivation of cover crops. However, there is limited research specifically addressing the potential of cover crops to enhance carbon inputs under the conditions of northern Italy in the Po Valley. An analysis from western Germany found a 12 % increase in carbon inputs from CC compared to the BAU scenario (Seitz et al., 2023). Due to the lack of specific data for the study area, a conservative value of 10 % increase in carbon inputs was assumed for the present analysis. The DPM/RPM ratio, which influences the rate of decomposition of plant material, is set to the default value of 1.44 for agricultural land, according to Coleman and Jenkinson (1996) and other studies (Jebari et al., 2021; Fantin et al., 2022).

Organic fertilization was modeled using regional data from the Po Valley (Italy). The application rate was assumed to be  $40 \text{ t ha}^{-1}$  of FYM, characterized by an average moisture content of 93.3 % and a carbon content on a dry basis of 33.1 % (Triberti et al., 2016). This resulted in a carbon input from FYM of  $0.89 \text{ tC ha}^{-1}$ . The contribution of FYM was intended as an additional carbon input which is assumed to be more decomposed than normal crop plant material. In the model, FYM was split into DPM 49 %, RPM 49 % and HUM 2 %, according to Coleman and Jenkinson (1996).

## 2.3. RothC input data

The model requires data on climate (air temperature, precipitation, and potential evapotranspiration) and soil (clay content and initial SOC content). Climate data, including temperature and precipitation, were obtained from the NASA Power Service (Hegyi et al., 2024). Potential evapotranspiration was calculated using the Penman-Monteith equation (FAO, 1998). Soil data, such as the initial SOC content in the topsoil (0–30 cm) and clay, were obtained from the International Soil Reference and Information Centre (ISRIC) SoilGrids 2.0, with a spatial resolution of 250 m (Poggio et al., 2021). Clay data are available at three different depths (0–5 cm, 5–15 cm and 15–30 cm) and were integrated over soil depths up to 30 cm using the trapezoidal rule (Bilas et al., 2022). RothC requires monthly Vegetation Cover (VC) information. VC data were obtained from the MOD13A2 Version 6 product, which provides the Normalized Difference Vegetation Index (NDVI) at a spatial resolution of 1 km (Didan, 2015). Google Earth Engine was used to retrieve satellite data and calculate the monthly probability of ground vegetation cover (NDVI > 0.6).

2.4. Life cycle assessment

Life Cycle Assessment is a scientific approach to decision making that quantifies the potential environmental impacts of products and services over their entire life cycle. The evaluation includes all stages of the product's life cycle, including raw material production, manufacturing, use, and end-of-life (Del Borghi, 2013). The steps involved in an LCA are the definition of the objective and scope, the inventory analysis, the impact assessment, and the interpretation of the results (ISO, 2006a,b).

For this LCA, the functional unit is defined as 1 ha of crop cultivation using conventional agriculture or CF practices. A cradle-to-farmgate methodology was chosen. Fig. 1 displays the processes that form part of the system boundaries. The supply and conversion of fuels, energy, and raw materials into finished agricultural equipment, infrastructure, and crop inputs—such as seeds, fertilizers, and tractors—are the background processes (Del Borghi et al., 2020). This study covers the following agricultural practices: tillage, sowing, crop protection, fertilizing, and harvesting.

Life Cycle Assessment (LCA) was conducted using SimaPro 10.2 software, with the Ecoinvent 3.11 database (Frischknecht and Rebitzer, 2005; Wernet et al., 2016) as the source of secondary life cycle inventory data. Environmental impacts were assessed using the Environmental Footprint 3.1 impact assessment methodology (JRC, 2023), and a subset of relevant impact categories was selected according to their relevance to agricultural systems.

The collection and processing of agricultural data for the LCA calculation focuses on the inventory data of the cultivation phase for the BAU scenario. The BAU scenario, which is the baseline, differs for each field but in most cases includes conventional tillage operations, no use of organic fertilizer, and no use of cover crops. This provided a baseline against which improvements and interventions in different scenarios could be assessed. The main data collected related to water, fertilizers, chemical treatments and diesel use. Secondary data, however, were used to model the quantity of seeds and seedlings. Primary data were collected directly from the HelpSoil project, while secondary data were collected from private industry reports and from the Ecoinvent database version 3.11. These are critical to developing a complete life cycle inventory and ensuring the accuracy of the data. The emissions due to fertilizer application were calculated according to the rules set out in the 2019 IPCC Guidelines, Volume 4: Agriculture, Forestry and Other Land Use (AFOLU), Chapter 11 (IPCC, 2019). Nutrient emissions were considered in terms of nitrate, phosphate, and gaseous emissions such as nitrous oxide from nitrogen fertilizer application. Both direct and indirect N<sub>2</sub>O emissions were accounted for. Indirect emissions included N<sub>2</sub>O emissions from the atmospheric deposition of N on soils and water surfaces, and emissions from N leaching and runoff. In most of the fields included in the study, all of the fertilizers used in the BAU scenario were inorganic, consisting of nitrogen-, phosphatic- and potassium-based

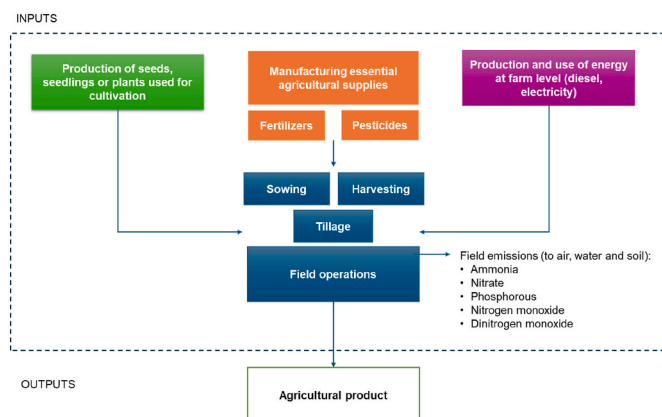
fertilizers. For each of the CF scenarios studied, the inventory data were modified, and assumptions were made to calculate the associated project emissions. The analysis considered the four scenarios presented in chapter 2.1: BAU, RT, CC and FYM, for which the detailed Life Cycle Inventory (LCI) is reported in Table 2.

In the CC scenario, emissions were primarily associated with additional field operations, including sowing, mowing, and biomass incorporation. These operations increase diesel consumption by approximately 30 L ha<sup>-1</sup> (after consultation with experts), resulting in indirect GHG emissions from diesel production and direct emissions during equipment use. While indirect GHG emissions from seed production were considered negligible, cover crops provide benefits such as improved soil organic matter, structure, and nutrient availability. The adoption of cover crops allows also for reductions in nitrate leaching in the order of 50–70 % (Nouri et al., 2022; Tonitto et al., 2006). To reflect this, the factor for nutrient losses reduction implied was 60 %. Other benefits of the use of cover crops are about improved water use, as cover

**Table 2**  
Life Cycle Inventory for the four scenarios analyzed.

INPUT	U. M.	BAU Scenario	CC Scenario	RT Scenario	FYM Scenario
Seeds/Seedling	kg ha <sup>-1</sup>	372.11	522.11	372.11	372.11
Diesel	l ha <sup>-1</sup>	71.51	92.96	35.75	71.51
Water	m <sup>3</sup> ha <sup>-1</sup>	1509.67	1283.22	1509.67	1509.67
Fertilizer: UREA	kg ha <sup>-1</sup>	79.25	79.25	79.25	30.70
Fertilizer: Ammonium Nitrate	kg ha <sup>-1</sup>	16.52	16.52	16.52	5.90
Fertilizer: nitrogen based	kg ha <sup>-1</sup>	17.66	17.66	17.66	6.70
Fertilizer: Phosphoric Anhydride	kg ha <sup>-1</sup>	20.16	20.16	20.16	8.01
Fertilizer: Diammonium phosphate	kg ha <sup>-1</sup>	8.23	8.23	8.23	3.29
Fertilizer: Ammonium sulphate	kg ha <sup>-1</sup>	2.08	2.08	2.08	0.83
Fertilizer: Potassium oxide	kg ha <sup>-1</sup>	12.91	12.91	12.91	5.13
Fertilizer: Potassium chloride	kg ha <sup>-1</sup>	11.25	11.25	11.25	4.50
Fertilizer: Organic	kg ha <sup>-1</sup>	4573.86	4573.86	4573.86	40000.00
Pesticides	kg ha <sup>-1</sup>	9.95	19.90	9.95	9.95
<b>Nutrient/toxicity emissions</b>					
NH <sub>3</sub> to air	kg ha <sup>-1</sup>	20.80	20.80	20.80	56.41
NO to air	kg ha <sup>-1</sup>	24.63	24.63	24.63	117.87
NO <sub>3</sub> <sup>-</sup> to water	kg ha <sup>-1</sup>	98.78	59.27	98.78	589.17
P to water	kg ha <sup>-1</sup>	1.52	1.52	1.52	0.61
Pesticides	kg ha <sup>-1</sup>	9.95	19.90	9.95	9.95
<b>GHG emissions</b>					
Direct N <sub>2</sub> O from soils	kg ha <sup>-1</sup>	3.62	3.62	3.62	6.49
N <sub>2</sub> O from N deposition	kg ha <sup>-1</sup>	0.29	0.29	0.29	1.01
N <sub>2</sub> O from NO <sub>3</sub> <sup>-</sup> leaching/runoff	kg ha <sup>-1</sup>	0.17	0.10	0.17	1.00

Note: BAU, Business-As-Usual; RT, Reduced Tillage; CC, Cover Crops; FYM, FarmYard Manure.



**Fig. 1.** Life Cycle Assessment system boundaries.

crops can reduce water requirements. In fact, literature on irrigated systems shows that the use of cover crops can decrease the annual irrigation demand by 10–25 % compared to bare-fallow fields (Gabriel et al., 2012; Novara et al., 2021). Based on this evidence, in the CC scenario irrigation requirements are lowered by 15 %. Other input data, with the exception of diesel consumption, leaching of nutrients, water use and pesticide application, were assumed to be unchanged from the BAU scenario.

In the RT scenario, project emissions account for reduced diesel consumption due to fewer tractor passes in the field. Based on literature values, reduced tillage can decrease fuel use by approximately 50 % compared to conventional practices (Lal, 2004; Keshavarz Afshar and Dekamin, 2022). Therefore, a 50 % reduction in diesel consumption has been applied in this scenario. All other input data, except diesel consumption, were assumed to be unchanged from the BAU scenario (Table 2).

In the FYM scenario, emissions considered include those associated with the use of agricultural machinery to apply organic fertilizer, as well as emissions from the fertilizers. These include indirect greenhouse gas (GHG) emissions of organic fertilizers (no upstream impact allocated, including only transport to the farm) and direct emissions to air and water after application. As the substitution of inorganic fertilizers is partial (ensuring appropriate N-P-K levels), the emissions from fertilizer application have been treated as substitution rather than additional emissions compared to the BAU scenario, with an unchanged total amount of fertilizer. Emissions to air and water from the use of organic fertilizers were calculated according to IPCC guidelines. For direct emissions calculation an average 0.6 % nitrogen content was assumed.

## 2.5. Integration of model simulations and life cycle assessment

The RothC model simulates SOC dynamics. Each scenario in this study provides an estimate of the annual carbon sequestered in the soil or lost to the atmosphere (referred to as the annual delta SOC change and expressed in  $t\ C\ ha^{-1}\ yr^{-1}$ ). Therefore, the average of the annual SOC changes over the study period was used to calculate the mean delta SOC change. To integrate the soil carbon dynamics results with the LCA results, the Carbon Footprint approach is used (Cammara et al., 2025), which allows the calculation of net GHG emissions expressed as  $t\ CO_2\ eq\ ha^{-1}\ yr^{-1}$ . The atomic masses of carbon ( $12\ g\ mol^{-1}$ ) and carbon dioxide ( $44\ g\ mol^{-1}$ ) were used to convert the mean delta SOC change to  $t\ CO_2\ eq\ ha^{-1}\ yr^{-1}$ , along with the Global Warming Potential – 100 years (GWP) of carbon dioxide per unit equal to one, with the following equation:

$$CO_2 - eq\ (ha^{-1}yr^{-1}) = C \times \frac{44}{12} \quad (\text{Eq. 2})$$

where C is the mean annual SOC stock change simulated by RothC-26.3 ( $t\ C\ ha^{-1}\ yr^{-1}$ ), i.e., the average of the annual delta SOC changes over the study period, which represent the only mechanism through which soils can act as a long-term sink for atmospheric  $CO_2$ . In parallel, the LCA framework comprehensively accounts for all greenhouse gas (GHG) emissions associated with agricultural inputs and field processes, including  $CO_2$ ,  $CH_4$ , and  $N_2O$ .

To obtain the net CB (Eq. (3)), SOC stock changes from RothC were expressed in  $CO_2$  equivalents and compared directly to the total GHG emissions from the LCA. This integration is methodologically consistent, as all fluxes are converted to the same metric ( $CO_2\ eq$ ), and reflects the fact that soil sequestration is the only biophysical mitigation service, whereas the farming system generates multiple GHG emissions. The purpose of this combined approach is not to homogenize emission sources, but rather to evaluate whether the SOC sequestration potential can offset the GHG emissions of the system over its entire life-cycle. The CB was then obtained by adding the carbon input (from the soil carbon models) and the carbon output (from the LCA):

$$CB[CO_2\ ha^{-1}yr^{-1}] = C_{Ei} - C_{Si} \quad (\text{Eq. 3})$$

where  $C_E$  is the  $CO_2$ -equivalents emitted to the atmosphere by the i-scenario and  $C_{Si}$  is the  $CO_2$ -equivalents that are either sequestered in the soil (i.e. negative impact on CB) or lost to the atmosphere (i.e. positive impact on CB). In this study,  $C_E$  denotes the total life-cycle climate change impact (total GHG emissions) returned by the LCA model. It aggregates direct on-field and upstream supply-chain emissions for inputs and operations, and is expressed in  $t\ CO_2\ eq\ ha^{-1}\ yr^{-1}$ .  $C_{Si}$  is taken as a positive value when C is sequestered and as a negative value when the soil is a source of emissions. The dynamic (i.e., C sequestered or lost on an annual basis) output of the carbon models was averaged over years to allow combination with the LCA output.

In addition to GHG emissions to the atmosphere, the following environmental impact indicators were assessed: Acidification, Water use, Resource use (fossil), Photochemical ozone formation, Land Use and Eutrophication (terrestrial). These results are not directly linked to the SOC results but should be seen as additional key information. As such, they can provide a broader view of the environmental impacts associated with the implementation of CF practices. This view provides insight into whether these practices actually benefit the environment or simply shift environmental impacts to other environmental compartments.

## 2.6. Statistical and uncertainty analysis

The outputs of the RothC model were subjected to a statistical analysis of the dynamics of SOC. Cumulative changes in SOC over 20 years ( $\Delta SOC$ ,  $t\ C\ ha^{-1}$ ) were computed at 16 independent field points for each management scenario (BAU, CC, FYM, and RT). Box-and-whisker plots were used to visualize the distributions and compute descriptive statistics, including the mean, standard deviation, standard error, and 95 % confidence intervals. A repeated-measures ANOVA was applied to test for differences among management practices, with significance assessed at  $\alpha = 0.05$ . To assess the impacts of management practices, effect sizes (partial  $\eta^2$ ) were reported. To evaluate temporal sequestration dynamics, SOC trajectories were also used to derive linear slope analysis ( $t\ C\ ha^{-1}\ yr^{-1}$ ) and the area under the curve (AUC,  $t\ C\ ha^{-1}\ 20\ yr^{-1}$ ).

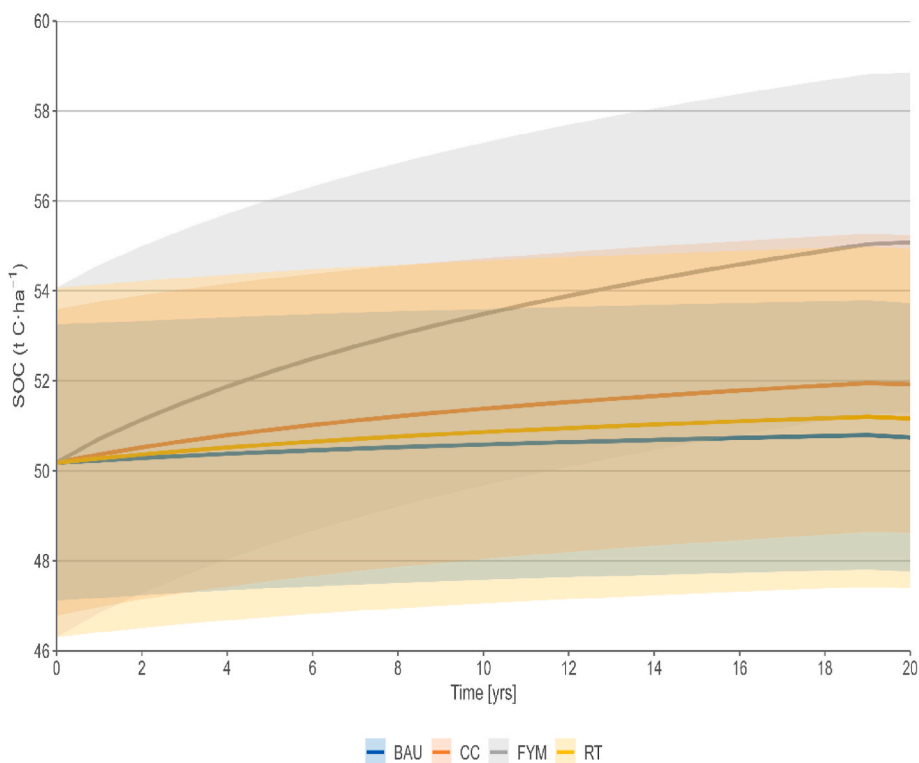
SimaPro 10.2 was used to perform uncertainty analysis for the life cycle assessment (LCA) at a 95 % confidence level using a Monte Carlo simulation ( $n = 2500$  runs). Through the inventory and impact assessment, this method spreads model uncertainty and parameter variability, yielding probability distributions for the environmental impacts evaluated. Finally, the standard deviation (SD) and the coefficient of variation (CV) were computed. Both statistical variability and model uncertainty were specifically addressed in the integrated carbon balance by integrating LCA-derived emission estimates with RothC-based SOC sequestration results.

## 3. Results

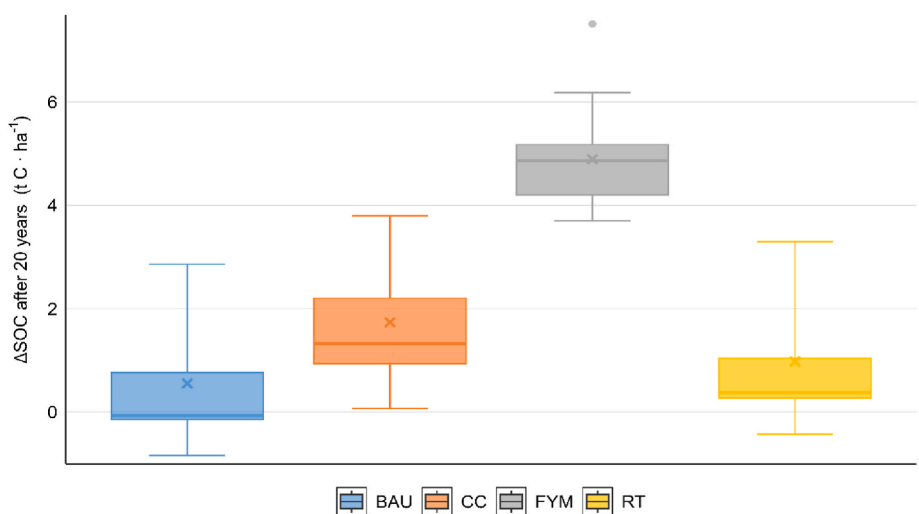
### 3.1. Soil organic carbon

The RothC model outputs the total SOC stock ( $t\ C\ ha^{-1}$ ) in the topsoil (0–30 cm). Across the 20-year simulation period, all scenarios displayed a positive trend in SOC accumulation, though with different magnitudes depending on the management practice (Fig. 2). The BAU scenario showed only a slight increase, while all CF practices enhanced SOC storage compared to BAU.

To compare overall sequestration performance among scenarios, the mean  $\Delta SOC$  after 20 years was calculated (Fig. 3). The BAU scenario resulted in a mean increase of  $0.55\ t\ C\ ha^{-1}$  ( $\pm 0.31\ t\ C\ ha^{-1}$ ), whereas CC led to an increase of  $1.73\ t\ C\ ha^{-1}$  ( $\pm 0.30\ t\ C\ ha^{-1}$ ). Farmyard Manure showed the highest SOC accumulation with  $4.89\ t\ C\ ha^{-1}$  ( $\pm 0.24\ t\ C\ ha^{-1}$ ), while RT resulted in a mean increase of  $1.34\ t\ C\ ha^{-1}$



**Fig. 2.** Simulated soil organic carbon (SOC) stocks ( $t C \cdot ha^{-1}$ ) in the 0–30 cm soil layer over a 20-year period under different management scenarios: Business as Usual (BAU), Cover Crops (CC), Farmyard Manure (FYM), and Reduced Tillage (RT). Lines represent mean values across replicates and shaded bands represent the error.



**Fig. 3.** Distribution of cumulative SOC changes ( $\Delta SOC$ ,  $t C \cdot ha^{-1}$ ) after 20 years for each management scenario. Boxplots show the interquartile range (25th–75th percentile, Q1 – Q3), horizontal lines represent medians, whiskers indicate non-outlier range, points are outliers; mean markers are shown.  $n = 16$  per scenario.

( $\pm 0.32 t C \cdot ha^{-1}$ ).

The distribution of SOC changes across replicates for each scenario is represented by the box-and-whisker plots (Fig. 3). The crosses represent the mean values. This graphical representation not only highlights the central tendency of SOC changes, but also illustrates the variability among the simulations, providing a comprehensive overview of the modeled outcomes.

The descriptive statistics and ANOVA of the cumulative change in soil organic carbon ( $\Delta SOC$ ) after 20 years for the four management scenarios ( $n = 16$  independent field points per scenario) are reported in Table 3. A repeated-measures ANOVA showed a highly significant effect of management on cumulative  $\Delta SOC$  ( $p < 1 \times 10^{-18}$ ), with partial  $\eta^2 =$

**Table 3**  
Descriptive statistics and ANOVA for the RothC simulation outcomes.

Scenario	BAU	CC	FYM	RT
Descriptive Statistics				
Mean $\Delta SOC$ ( $t C \cdot ha^{-1}$ )	0,56	1,74	4,89	0,98
Standard Deviation ( $t C \cdot ha^{-1}$ )	1,25	1,19	0,97	1,30
Standard Error ( $t C \cdot ha^{-1}$ )	0,31	0,30	0,24	0,32
C.I. 95 % ( $t C \cdot ha^{-1}$ )	0,67	0,63	0,52	0,69
ANOVA				
$p$ -value	$5,76 \times 10^{-19}$			
Partial $\eta^2$	0,86			

0.86 indicating a very large effect size. The FYM treatment shows a distinct and significantly higher SOC accumulation compared to the other scenarios, while CC and RT present intermediate performances between FYM and BAU.

The results of the slope analysis indicate the annual rate of SOC sequestration under different agricultural practices (Table 4), with FYM demonstrating the highest average annual increase ( $0.24 \text{ t C ha}^{-1} \text{ yr}^{-1}$ ), significantly outperforming conventional agriculture (BAU,  $0.03 \text{ t C ha}^{-1} \text{ yr}^{-1}$ ). The AUC values, which represent the cumulative SOC sequestration over 20 years, further confirm these findings, with FYM accumulating nearly nine times more carbon than BAU. Cover crops (CC) and reduced tillage (RT) provide moderate improvements but remain substantially lower than FYM.

### 3.2. Life cycle assessment

The full set of environmental impact indicators from the LCA analysis is reported in Table 5, presenting average values, standard deviations (SD), and coefficient of variation (CV) from the uncertainty analysis across all scenarios. Table 5 includes eleven environmental impact categories that capture different aspects of agricultural system performance beyond climate change. These categories were selected to provide a comprehensive view of potential environmental burdens across multiple emission pathways and environmental compartments: atmospheric impacts (acidification, photochemical ozone formation), aquatic impacts (eutrophication in marine and freshwater environments), terrestrial impacts (terrestrial eutrophication), resource depletion (fossil fuel consumption), and water consumption.

The LCA results (Table 5) demonstrate substantial variation in environmental impact magnitudes across the four management scenarios. Climate change impacts ranged from  $2.12 \text{ t CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$  for RT to  $3.25 \text{ t CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$  for FYM, with BAU and CC showing intermediate values ( $2.30$  and  $2.31 \text{ t CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$ , respectively). However, the magnitude of differences varies dramatically across impact categories. For acidification, impacts ranged from  $41.13 \text{ mol H}^+\text{-eq}$  (RT) to  $150.53 \text{ mol H}^+\text{-eq}$  (FYM), representing approximately 3.7-fold variation. Marine eutrophication showed even greater variation, ranging from  $40.26 \text{ kg N-eq}$  (CC) to  $215.25 \text{ kg N-eq}$  (FYM), a 530 % difference.

The breakdown of the main GHG emission sources is shown in Fig. 4. In all scenarios, direct emissions from fertilizers are the main source of carbon emissions, accounting for more than 40 % of the total emissions and reaching 71 % in the FYM scenario. The other relevant sources of carbon emissions are in descending order: fertilizer production, diesel consumption for field operations, pesticides, and seeds or seedlings.

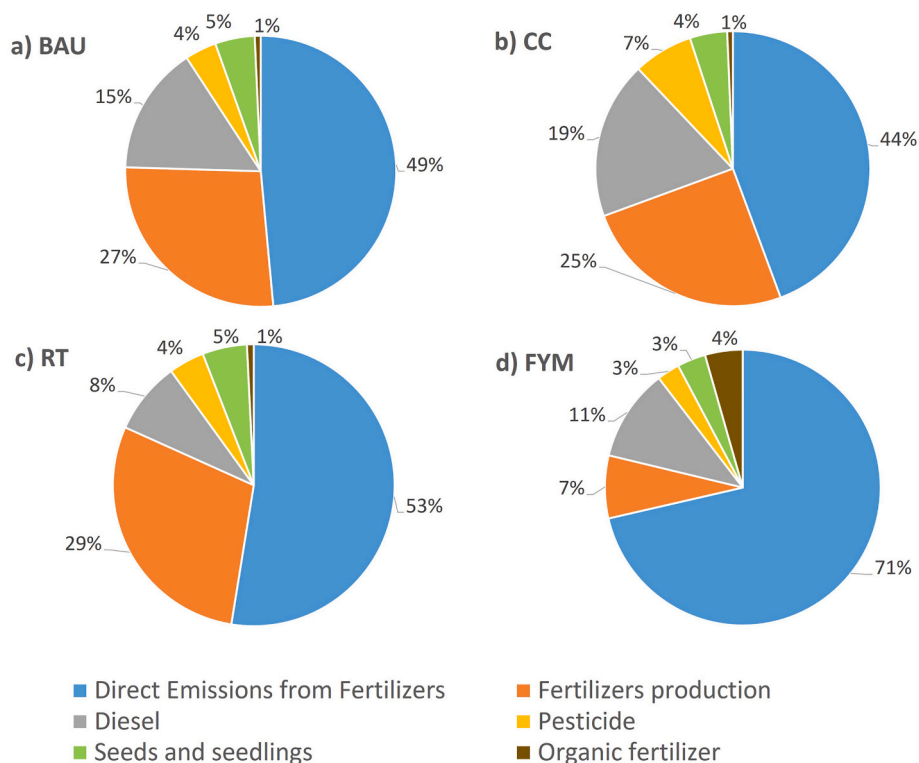
Reduced tillage emerges as the most robust strategy, demonstrating consistent environmental benefits across acidification, eutrophication, and photochemical ozone formation categories (all reduced relative to BAU) while achieving  $-20.4 \%$  lower fossil fuel consumption ( $16,614 \text{ MJ ha}^{-1} \text{ yr}^{-1}$ ) and maintaining the lowest model uncertainty (CV  $0.98\text{--}11.20 \%$ ). Farmyard manure maximizes environmental burdens, with dramatic increases across acidification ( $+254 \%$ ), marine eutrophication ( $+372 \%$ ), terrestrial eutrophication ( $+243 \%$ ), and photochemical ozone formation ( $+290 \%$ ), despite achieving the lowest fossil fuel demand ( $15,025.7 \text{ MJ ha}^{-1} \text{ yr}^{-1}$ ). Cover crops present a polarized profile: delivering marine eutrophication and water use improvements ( $-11.7 \%$  and  $-14.7 \%$ , respectively) while incurring acidification and

**Table 4**  
Slope and AUC values for the four investigated scenarios.

Scenario	Slope ( $\text{t C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ )	AUC ( $\text{t C}\cdot\text{ha}^{-1}\cdot 20 \text{ yr}^{-1}$ )
BAU	0,03	7,37
CC	0,09	22,06
RT	0,05	12,50
FYM	0,24	60,99

**Table 5**  
Life Cycle Impacts for the four analyzed scenarios (FU: 1ha), table reports the average, SD and CV coming from the uncertainty analysis.

Impact Category	U.M.	BAU			CC			RT			FYM		
		Average	SD	CV	Average	SD	CV	Average	SD	CV	Average	SD	CV
Acidification	$\text{mol H}^+\text{-eq}$	42.51	1.52	3.58 %	47.01	1.73	3.68 %	41.13	1.12	2.72 %	150.53	1.08	0.72 %
Climate change	$\text{t CO}_2\text{-eq}$	2.30	0.19	8.19 %	2.31	0.21	9.08 %	2.12	0.17	7.93 %	3.25	0.15	4.58 %
Eutrophication, marine	$\text{kg N-eq}$	45.58	0.12	0.27 %	40.26	0.17	0.41 %	45.04	0.12	0.27 %	215.25	0.11	0.05 %
Eutrophication, freshwater	$\text{kg P-eq}$	1.90	1.29	67.73 %	2.00	1.65	82.44 %	1.88	1.10	58.53 %	0.95	1.18	124.58 %
Eutrophication, terrestrial	$\text{mol N-eq}$	371.18	5.23	1.41 %	387.45	7.58	1.96 %	365.32	3.59	0.98 %	1274.34	4.99	0.39 %
Land use	Pt	61322.53	129000.00	210.36 %	65378.23	128000.00	195.78 %	58802.07	116000.00	197.27 %	60927.37	122000.00	200.24 %
Ozone depletion	$\text{kg CFC}_{11}\text{-eq}$	2.01E-04	7.77E-05	38.72 %	3.71E-04	1.70E-04	45.83 %	1.98E-04	9.28E-05	46.78 %	1.93E-04	8.71E-05	45.23 %
Particulate matter	disease inc.	5.81E-04	2.13E-05	3.66 %	6.11E-04	2.03E-05	3.32 %	5.73E-04	1.68E-05	2.93 %	1.46E-03	1.51E-05	1.03 %
Photochemical ozone formation	$\text{kg NMVOC-eq}$	32.11	1.34	4.17 %	33.92	1.61	4.75 %	30.33	0.75	2.47 %	125.22	1.21	0.97 %
Resource use, fossils	MJ	18883.64	1650.00	8.74 %	22228.64	2190.00	9.85 %	16614.00	1860.00	11.20 %	15025.70	1540.00	10.25 %
Water use	$\text{m}^3 \text{ depriv.}$	69319.67	13400.00	19.33 %	59162.58	14200.00	24.00 %	69305.65	11200.00	16.16 %	68905.67	10600.00	15.38 %



**Fig. 4.** Climate change impact: contribution of emission sources for four land management scenarios (BAU, CC, FYM, RT), expressed in  $t\ CO_2\text{-eq}\ ha^{-1}\ yr^{-1}$ . Each segment represents the share of total GHG emissions from each source category. a) BAU, Business As Usual; b) CC, cover Crops; c) RT, Reduced Tillage; d) FYM, FarmYard Manure.

terrestrial eutrophication penalties (+10.6 % and +4.4 %), coupled with the highest fossil resource use intensity ( $22,228.64\ MJ\ ha^{-1}\ yr^{-1}$ ).

### 3.3. Carbon balance

The carbon balance (CB) was calculated as the algebraic sum of carbon sequestration and system-wide GHG emissions, expressed on an annual basis over the 20-year modeling period. Soil organic carbon gains were converted to  $CO_2$  equivalents using Equation (2). All scenarios resulted in positive SOC sequestration, quantified in Table 6. BAU showed the lowest sequestration rate at  $0.10\ t\ CO_2\ ha^{-1}\ yr^{-1}$  ( $\pm 0.06$ ), while CC and RT achieved moderate sequestration of  $0.32\ t\ CO_2\ ha^{-1}\ yr^{-1}$  ( $\pm 0.05$ ) and  $0.25\ t\ CO_2\ ha^{-1}\ yr^{-1}$  ( $\pm 0.06$ ), respectively. FYM achieved the highest sequestration rate at  $0.90\ t\ CO_2\ ha^{-1}\ yr^{-1}$  ( $\pm 0.04$ ), representing a 9-fold increase over BAU.

Despite substantial differences in SOC sequestration rates (ranging from  $0.10$  to  $0.90\ t\ CO_2\ ha^{-1}\ yr^{-1}$ ), the net carbon balance remained relatively similar across scenarios ( $1.87$ – $2.08\ t\ CO_2\ ha^{-1}\ yr^{-1}$ ). This reflects a trade-off mechanism: while management practices such as FYM and CC enhanced soil carbon sequestration, they were partially offset by increased system-wide emissions. The FYM scenario shows highest sequestration but also highest total emissions at  $3.25\ t\ CO_2\ ha^{-1}\ yr^{-1}$ . Consequently, the ranking of scenarios by sequestration potential

**Table 6**

Carbon balance components for each scenario, sequestration potential, emissions, and net carbon balance.

Scenario	Carbon Sequestration ( $t\ CO_2\ ha^{-1}\ yr^{-1}$ )	Carbon Emissions ( $t\ CO_2\ ha^{-1}\ yr^{-1}$ )	Carbon Balance ( $t\ CO_2\ ha^{-1}\ yr^{-1}$ )
BAU	$0.10\ (\pm 0.06)$	$2.30\ (\pm 0.19)$	$2.08\ (\pm 0.20)$
CC	$0.32\ (\pm 0.05)$	$2.31\ (\pm 0.21)$	$1.91\ (\pm 0.22)$
RT	$0.25\ (\pm 0.06)$	$2.12\ (\pm 0.17)$	$1.87\ (\pm 0.18)$
FYM	$0.90\ (\pm 0.04)$	$3.25\ (\pm 0.15)$	$1.93\ (\pm 0.16)$

did not translate into proportional improvements in overall carbon balance.

## 4. Discussion

### 4.1. Soil organic carbon sequestration potential

Several agricultural management practices were assessed in previous research in relation to their sequestration potential, including agroforestry, hedgerow planting, cover crops, and reduced tillage, and demonstrated increases in SOC in several scenarios (Aertsens et al., 2013). The results of this study confirm that different land management regimes have significant impacts on soil carbon sequestration and GHG fluxes. The results of the RothC model reveal a general SOC increase across all scenarios, with the farmyard manure (FYM) scenario sequestering, on average, the most carbon ( $4.89\ t\ C\ ha^{-1}$ ) after 20 years. This is consistent with evidence indicating that organic amendments such as manure enhance soil carbon sequestration (Owusu et al., 2024). CC and RT also increase SOC, but to a lesser extent, confirming their value as sustainable options (Babu et al., 2023; Breil et al., 2023). The BAU scenario shows a moderate increase in SOC stocks. Although conventional agriculture is often associated with SOC losses (Francaviglia et al., 2018), in the BAU scenario the arable crop rotation included both maize and wheat which are known for adding large amounts of crop residues contributing to SOC (J. Wang et al., 2015) and some exogenous FYM was also included in the BAU scenario, since three of the farms were already using FYM as part of their fertilization strategy.

RothC-26.3 was configured for Northern Italian arable systems with a 20-year horizon and 0–30 cm topsoil, chosen to match policy-relevant evaluation windows (Ledo et al., 2020; Petersson et al., 2025) and to represent the management-responsive layer in Mediterranean croplands. RT, CC, and FYM were selected as complementary sequestration pathways and parameterized consistently with recent European RothC

adaptations (Pesce et al., 2024). These adaptations align SOC modeling with actionable agronomic levers in Northern Italy while extending prior syntheses that identify input-driven and disturbance-mediated pathways as primary routes to SOC gains in croplands. The carbon sequestration values in the topsoil obtained from the simulations performed in this study are in line with previous findings, which are in the same order of magnitude for FYM, CC and RT practices (Bolinder et al., 2020). In addition, nitrogen inputs from crop residues have the potential to control SOC stabilization in the long term (van de Vreken et al., 2016).

While this study successfully modeled SOC dynamics in the topsoil (0–30 cm) with regional relevance, future research should explore the role of lateral carbon fluxes in modeling SOC stocks. This can have an influence on soil erosion and affect sequestration estimates. If the study area is prone to erosion, including these variables could provide a more comprehensive view of SOC dynamics by taking into account both vertical and horizontal carbon fluxes in order to accurately estimate sequestration potential, further confirming the need for integrated assessments in soil carbon science (Nadeu et al., 2015). Restricting analysis to topsoil may underestimate SOC change, underscoring the importance of deeper carbon storage for long-term sequestration. Tillage depth is another important variable to consider. The results of this study relate to the first 30 cm of soil, but existing literature emphasizes the importance of including deeper soil horizons to fully quantify SOC stock changes (Ottoy et al., 2016). Future work could extend modeling to 0–60 or 0–100 cm using modified RothC parameterizations or comparable depth-differentiated approaches which would capture mineral-associated carbon stabilization in deeper horizons (Smith et al., 2010). Another important consideration is the potential influence of climate change on SOC dynamics. Conditions of turnover shifts could negatively affect efforts to increase carbon sequestration (Pohanková et al., 2022). As their study suggests, it will be essential to include future climate conditions, as these will affect long-term SOC stability and make SOC accumulation vulnerable to climate-induced shifts, confirming the relevance of climate adaptation strategies.

#### 4.2. Environmental trade-offs

He LCA results show that, under the modelling hypotheses of this study, the RT scenario has the lowest overall environmental impact, although it provides lower carbon sequestration than the other CF practices. In contrast, FYM achieves high carbon sequestration but also results in the highest GHG emissions, mainly due to the large quantity of fertilizers used. The prevalence of emissions from nitrogen fertilization—whether from mineral or organic sources—highlights the need to optimize fertilization strategies to minimize environmental trade-offs. Nitrogen losses through leaching and runoff pathways are not unique to manure but represent a broader challenge across all fertilization strategies; however, manure-based approaches typically exhibit higher nutrient loss rates due to elevated total nitrogen content and less controlled release patterns relative to granulated mineral fertilizers. The comprehensive environmental impact assessment reveals that FYM has significantly higher eutrophication (+372 %) and acidification (+254 %) potentials relative to BAU. These findings reveal that although FYM improves carbon sequestration in soils, it may have poorer overall environmental performance unless practices to reduce nutrient losses via runoff and emissions are applied. An important consideration regarding system boundaries emerges when contextualizing the FYM scenario within broader agricultural systems: the manure applied originates from livestock production, which itself generates substantial greenhouse gas emissions (enteric fermentation, manure management). This study follows an attributional LCA approach with a field-level system boundary, treating manure as a co-product with its burdens already allocated elsewhere in the supply chain. However, consequential LCA frameworks that extend the system boundary to include livestock production would potentially further increase emissions in the FYM scenario (Battini et al., 2016). This distinction is critical for

policy-makers evaluating CF schemes: the carbon sequestration benefits of FYM must be weighed against the full lifecycle emissions of the livestock system generating the manure, particularly in regions with intensive animal production (Singaravadivelan et al., 2023).

Given the critical importance of nitrate vulnerable zones in Northern Italy, the environmental trade-offs of FYM become especially pronounced. While the 254 % increase in acidification and 372 % increase in marine eutrophication represent substantial burdens, these impacts are particularly problematic in regions where groundwater is already vulnerable to nitrate contamination. In our study, we assumed an application rate of 40 t ha<sup>-1</sup> of FarmYard Manure as a strategy to increase carbon inputs into the soil and promote carbon sequestration. The authors recognize that this is a high application rate and acknowledge the complex relationship between carbon sequestration and nitrogen management. This issue becomes even more important in nitrate-vulnerable zones (Quilez et al., 2025). Manure-based fertilization contributes significantly to nitrate leaching to groundwater, with up to 20 % of groundwater sources exceeding safe nitrate thresholds. In addition, soil nitrogen saturation can lead to a number of negative effects, including soil acidification, nutrient imbalances, and increased nitrous oxide emissions. This trade-off underscores that while manure amendments can be beneficial for carbon sequestration, they can also increase nitrogen pollution, impacting both local water systems and the atmosphere. Consequently, the application of animal manure in nitrate-vulnerable areas must be carefully managed to optimize carbon sequestration while mitigating nitrogen-related environmental risks (Kros et al., 2024). CC and RT, on the other hand, have more evenly distributed effects, with CC providing benefits in terms of land-use efficiency, while RT shows less dependence on fossil resources due to reduced machinery use.

#### 4.3. System boundaries and lifecycle considerations

The LCA results indicate that while CF practices can build SOC, they also lead to higher emissions in many environmental impact categories. For these reasons, a comprehensive assessment of agricultural management is needed, as it is not sufficient to focus solely on carbon sequestration potential; potential negative side effects, such as increased GHG emissions from fertilization, must also be assessed. The results of this study are related to burden shifting considerations, where organic amendments such as manure have the potential to trigger increased nutrient leaching and emissions. The carbon balance calculation confirms that although all the scenarios lead to SOC gains, the net carbon balance is still positive because emissions have higher values than sequestration. This confirms the need for complementary mitigation measures, such as the use of carbon offset projects or increased soil amendment effectiveness, to achieve carbon neutrality.

The carbon balance (CB) can be interpreted as a single indicator offering an easy-to-read result for supporting decision makers and can be potentially integrated in more comprehensive evaluations, such as the Water-Energy-Food-Climate (WEFC) nexus (Moreschi et al., 2024). Obtained CB values are positive in all scenarios, i.e. the total emissions are higher than sequestration, but with different values between the scenarios. The maximum carbon sequestration value of 0.90 t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> is obtained from the FYM scenario, which is also characterized by the highest Carbon Footprint (2.38 t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>) and an overall better performance compared to the BAU scenario. The CC and RT scenarios also result in a lower CB than the BAU scenario, demonstrating their effectiveness for climate mitigation purposes. The CB concept, intended as a balance between carbon sequestration and carbon emissions, was introduced to assess the performance of regenerative agricultural practices in citrus production in Sicily (Italy) (Cammarata et al., 2025). While that context is not directly comparable to our arable system, those authors reported a more favorable CB under regenerative management. In our scenarios, CF practices increased SOC sequestration but the net CB remained similar across scenarios because higher

sequestration was offset by higher emissions. Another example of coupling carbon sequestration modelling (using the RothC model) with LCA showed that SOC sequestration can offset a significant part of the carbon footprint of the farming activity. For instance, in the case of olive groves, SOC in the soil up to 15 cm depth was the main driver for the large reduction in net GHG emissions, again confirming the proposition that SOC processes need to be included in product environmental footprints (PEF). However, as the RothC study on olive production suggests, the inclusion of SOC within PEF methodologies requires more site-specific information, which may prove challenging to obtain and analyze (Fantin et al., 2022).

#### 4.4. Limitations and implications for decision making on agricultural sustainability

The limitations of this study are primarily related to modelling choices. The RothC configuration used in this study represents the average SOC dynamics in non-waterlogged topsoil. It does not, however, explicitly capture subsoil processes, erosion-driven lateral carbon redistribution, or fine-scale spatial heterogeneity. Therefore, SOC estimates are more robust at the system level than at the field or plot scale (Wang et al., 2015b). The analysis is restricted to the 0–30 cm layer and a 20-year time horizon, which may underestimate total SOC changes in systems where deeper mineral-associated carbon contributes substantially. It also does not fully reflect potential long-term saturation or legacy effects under changing climate conditions (Wan et al., 2011). In addition, the attributional, field-level LCA omits broader market responses and only partially reflects upstream livestock emissions through the selected allocation rules. This implies that the climate and eutrophication burdens of manure-intensive strategies could be underestimated when viewed from a full supply-chain or consequential perspective. Finally, the model is parameterised for Northern Italian maize–wheat rotations and a specific FYM application rate. Therefore, extrapolation to other pedoclimatic conditions, crop systems, and regulatory contexts (e.g. stricter manure limits) should be interpreted with caution (Guerrieri et al., 2026).

Within this context, the findings of this study have several important implications for agricultural policy and practice aimed at mitigating climate change through CF. Rather than prescribing a single “best practice”, the results point towards context-dependent decision-making that considers trade-offs across multiple environmental dimensions. In regions, where the primary objective is carbon sequestration (e.g. through carbon markets or compliance schemes), cover crops emerge as a balanced approach, delivering moderate sequestration ( $0.32 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ ) while minimising negative environmental impacts. Reduced tillage provides benefits through fossil fuel reduction. In contrast, high-rate manure application should be reserved for regions where local or regional nitrogen saturation is not a concern where nitrogen-vulnerable zone restrictions do not apply and where livestock production systems already exist, thereby avoiding net lifecycle emission increases. The carbon balance metric used in this study offers a pragmatic tool for comparing management scenarios but the results should not be interpreted as indicating complete carbon neutrality or climate benefit. As mentioned previously, CF practices in this study reduce net emissions relative to BAU but do not achieve a zero or negative carbon balance. These findings have direct implications for designing carbon farming schemes and certification frameworks in Europe, including those emerging under the EU Carbon Removal Certification Framework (CRCF). If incentives and credits are granted solely on the basis of SOC increases, the application of high-rate manure may be encouraged, despite this causing substantial nitrogen pollution and providing only partial net climate benefits, especially when upstream livestock emissions are fully accounted for. For agricultural systems to meaningfully contribute to climate targets, additional mitigation measures will likely be necessary alongside soil carbon building, such as precision nutrient management to reduce losses, renewable energy adoption for farm

operations, or dietary shifts reducing livestock dependence.

## 5. Conclusions and future perspectives

This study demonstrates that agricultural management strategies can generate measurable soil organic carbon (SOC) gains, but with context-dependent trade-offs. For carbon farming (CF), overall environmental performance should be evaluated, as CF may place too much emphasis on carbon sequestration without fully considering other environmental impacts that require mitigation. Decision-makers should therefore adopt a multi-criteria assessment framework rather than optimize a single indicator, in order to provide a more comprehensive assessment of agricultural sustainability. CF should be viewed as one tool within a broader portfolio of agricultural, dietary and energy-system changes necessary to meet climate targets. Future research must address critical limitations related to climate-adaptation dynamics, to ensure SOC stability under future conditions, and improve monitoring, reporting and verification (MRV) technologies, including remote sensing and machine learning, to enhance SOC inventory accuracy and policy enforcement. Effective policy design also requires integration of CF into existing instruments (e.g. the Common Agricultural Policy and the Carbon Removal Certification Framework), with explicit recognition of the associated environmental trade-offs. Long-term incentives that balance sequestration goals with farmer profitability are essential, as SOC saturation occurs over decades. Optimised nitrogen management—through precision application, manure-management controls and combined practices such as reduced tillage and agroforestry—can prevent environmental degradation while sustaining SOC gains. Integrating Life Cycle Assessment offers a pathway toward comprehensive sustainability assessment but requires resolving methodological issues related to permanence, data availability and social-equity dimensions. Aligning research, technology development and policy timelines will enable agricultural systems to evolve towards sustainability without compromising soil health or long-term productivity.

### CRedit authorship contribution statement

**Stefano Spotorno:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anne Gobin:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Diego Armando Arellano Vazquez:** Data curation, Conceptualization. **Erica Gagliano:** Writing – review & editing, Writing – original draft, Conceptualization. **Adriana Del Borghi:** Supervision, Conceptualization. **Michela Gallo:** Writing – review & editing, Supervision.

### Data availability statement

The data presented in this study are available on request from the corresponding author.

### Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT v5.0 in order to improve text fluency. After using this tool/service, the author (s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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