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Evaluating the impact of soil conservation measures on soil organic carbon at the farm scale

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ABSTRACT

No-tillage (NT) is considered the least invasive conservation agriculture technique and has shown to be the effective in increasing soil C stocks, and reducing losses compared to others tillage systems. In Italy, the Veneto Region was the first to establish a subsidies scheme aimed at promoting the adoption of NT practices. This program encourages farmers to perform direct seeding, alternate autumn and winter crops and maintain soil cover throughout the year by leaving crop residues or sowing cover crops.

The goals of this study were to: (i) compare the CO_2 emission and soil C sequestration patterns of agricultural soils under CT and NT management practices in the Veneto region and (ii) analyse the potential mid-term benefits (2010–2025) of NT management in terms of soil organic C dynamics and CO_2 balance. Agronomic data and soil organic carbon levels were measured from 2010 to 2014 in eight farms in the Veneto region that had adopted CT and NT techniques. Field measurements were used to calibrate first and then validate the SALUS model to compare the mid-term impact of CT and NT practices using climate projections. SOC carbon pools in the model were initialized using the procedure described in Basso et al. (2011c). This is the first study to employ a model using such an extensive dataset at the farm level to assess the CT and NT strategies within this region.

Results of this research will assist farmers and policy makers in the region to define the tillage systems most suited to improve soil C stocks and thereby minimize CO_2 emissions from agricultural soils. Overall, simulations indicated that SOC stocks can decrease under both CT and NT regimes, however SOC oxidation rates were substantially lower under NT. Critically, the greatest reduction in CO_2 emission was observed when NT was adopted in soil with high levels of SOM. This highlights the benefits of NT adoption in terms of soil fertility preservation and CO_2 emissions mitigation.

1. Introduction

Interest in finding techniques that reduce carbon dioxide (CO_2) emission or increase CO_2 sequestration has greatly increased in recent years (Sundermeier et al., 2005; Baker et al., 2007; Lal, 2009; Guzman and Al-Kaisi, 2010). Specifically, sequestration of carbon (C) in soil has become a topic of considerable debate within the international scientific community as it offers substantial advantages for agriculture and can help to mitigate the effects of climate change (Olson, 2014).

Tillage operations typical of conventional tillage regimes (CT), such as ploughing and seed bed preparation, lead to intense oxidation rates of soil organic matter (Al-Kaisi and Yin, 2005) which results in the release of substantial amounts of CO_2 to the atmosphere (Marinello et al., 2017). Conversely, significant reductions in CO_2 emissions and increased levels of soil organic C (SOC) have been observed when conservative soil management techniques have been adopted (Lal et al., 2003).

No tillage (NT) is considered the least invasive conservation agriculture technique and has shown to be the most effective in increasing soil C stocks, thereby abating CO_2 emissions, or at least reducing losses compared to others tillage systems (Pacala and Socolow, 2004; Puget and Lal, 2005; Senthilkumar et al., 2009; Luo et al., 2010). Key principles of NT practices are: (i) the absence of any soil disturbance apart from planting, (ii) permanent soil cover between cropping seasons achieved by cover crops or by retaining at least 30% of crop residues on the soil at harvest and

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iii) adopting crop rotations that include the succession of different crops.

The effectiveness of NT in sequestering atmospheric C has led many national and regional governments to promote this practice (Pezzuolo et al., 2014). In Italy, the Veneto Region was the first to establish a subsidies scheme aimed at promoting the adoption of NT practices (norm 214/I - Act 1 of the Veneto Rural Development Program 2007–2013). This program encourages farmers to perform direct seeding, alternate autumnal and winter crops and maintain soil cover throughout the year by leaving crop residues or sowing cover crops.

However, the debate on the real effectiveness of NT in increasing soil C stocks is still open (Dimassi et al., 2014). Studies supporting the positive effects of NT on soil C (Lal, 2004) have been countered by studies that report no net C sequestration when compared to CT (Blanco-Canqui and Lal, 2008). There have also been studies that show both CT and NT systems may lead to soil C losses (Kumar et al., 2012) even though these studies were conducted under diverse field conditions (e.g. local climate, soil type, crop rotations), which makes a direct comparison or generalization of results more difficult. There is therefore an urgent need to compare the agronomic and environmental performances of CT and NT at a regional scale and under varying climatic conditions, to provide clear analysis and guidance to local farmers and policy makers.

The goals of this study were to: (i) compare the CO_2 emission and sequestration patterns of agricultural soils under CT and NT management practices in the Veneto region and (ii) analyse the potential mid-term benefits (2010–2025) of NT management in terms of soil organic C dynamics and CO_2 balance. Agronomic data and soil organic carbon levels were measured from 2010 to 2014 in eight farms in the Veneto region that had adopted CT and NT techniques. Field measurements were used to calibrate first and then validate the SALUS model to compare the mid-term impact of CT and NT practices using climate projections. SOC carbon pools in the model were initialized using the procedure described in Basso et al., 2011c). This is the first study to employ a model using such an extensive dataset at the farm level to assess the CT and NT strategies within this region. Results of this research will assist farmers and policy makers in the region to define the tillage systems most suited to improve soil C stocks and thereby minimize CO_2 emissions from agricultural soils.

2. Material and methods

2.1. Study sites and experimental settings

Measurements and technical data relative to the adoption of CT and NT practices were collected from 2010 to 2014 in eight different farms in the Veneto region. The crops monitored, wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), Soybean (*Glycine max* L.) and Rapeseed (*Brassica napus* L.), are the crops most extensively grown in the region.

Data recorded at each farm included soil characteristics, climate, tillage events, machinery (e.g. power, working capacity), crop varieties, seeding density, fertilizer and pesticide applications and yields, as well as the timing of every farming operation. Detailed information on average agricultural practices for CT and NT adopted at the eight farms is reported in Table 1. Crop rotations differed slightly across farms (Table 2) but generally consisted of three-year or four-year cycles which included wheat or rapeseed, soybean and maize. Additionally, ryegrass, barley and vetch were grown as cover crops in the NT treatments.

Climate statistics (Table 3) include averages for minimum and maximum temperature, precipitation and solar radiation which were computed for each farm using a minimum of 10 years of daily data. The data were obtained from ARPAV (Regional Agency for Environmental Protection and Prevention of Veneto) weather stations located within 5 km from each farm. Soil data included profile depth, presence of stones, texture, soil organic matter (SOM), pH, total nitrogen, available phosphorus, cation exchange capacity (CEC) and bulk density (Table 3).

2.2. Energy requirement and C emission analysis

Overall CO_2 emissions were estimated for each tillage systems assessing the energy requirements of farming operations and products applied, as well as the CO_2 emitted by the soil due to specific land management practices (i.e. tillage and residue management).

CO_2 emissions attributed to farming operations were determined by taking into consideration both direct and indirect energy requirements (Table 4). Direct energy requirements included fuel consumption due to management operations and desiccation of harvested material, while indirect energy requirements included fertilizer and pesticide production and machinery construction. The energy requirements (MJ kg^{-1}) and CO_2 emissions (kg C kg^{-1} product) of each farming operation and input were estimated using energy conversion coefficients as described in Pimentel and Pimentel, 1979; Clements et al., 1995; West and Post, 2002. Soil-derived CO_2 emissions and atmospheric C sequestration into the SOC matrix were determined using the calibrated SALUS model (Basso et al., 2006; Senthilkumar et al., 2009; Basso and Ritchie, 2015).

The analysis of energy requirements and CO_2 emissions was not extended beyond the point of agricultural production for practical reasons. Consequently, energy consumption and emissions related to marketing and product distribution were excluded from the analysis and are assumed to be identical for both tillage regimes. Moreover, this study focused on "anthropic" inputs of the agronomic practices studied. Unlike other approaches for the computation of energy requirement and CO_2 emission balances, the "natural" inputs from the environment (e.g. solar radiation, wind, water) were therefore not considered.

2.3. The SALUS model

The SALUS soil-crop model (System Approach to Land Use Sustainability) is derived from the CERES model (Ritchie and Otter, 1985), and it has been specifically designed to simulate crop, soil, water and nutrient dynamics under different management strategies over multiple years (Basso et al., 2015; Basso and Ritchie, 2015). The model was designed to take into account several aspects of crop and land management such as crop rotations, planting dates, plant populations, irrigation and fertilizer applications, and tillage regimes (Basso et al., 2006). Submodels of SALUS are executed using daily time steps for major components of the crop-soil-water system including water balance, soil organic matter, nitrogen and phosphorous dynamics, heat balance, plant growth and plant development (Fig. 1). SALUS allows for different management strategies to be run simultaneously, thereby allowing their comparison under the same weather sequence. The water balance submodel simulates surface runoff, infiltration, surface evaporation, saturated and unsaturated soil water flow, drainage, root water uptake, soil evaporation and transpiration. The soil organic matter and nutrient submodel simulates organic matter decomposition, N mineralization, nitrification and denitrification, N immobilization, gaseous N losses and three pools of phosphorous.

SALUS has been widely used (Basso and Ritchie, 2015) and successfully validated for Italian agricultural systems and environmental conditions by Basso et al. (2007, 2010, 2011, 2011b, 2016).

Table 1
Average agricultural practices adopted under the CT and NT regimes at the eight farms investigated. Data refer to the period 2010–2014.

Crop	CT				NT			
	Wheat	Soybean	Maize	Rapeseed	Wheat	Soybean	Maize	Rapeseed
Tillage	Mold-board plough, Chisel, Rotary harrow				–			
Cover crops Fertilizer [kg ha^{-1}]		–			Ryegrass, barley and/or vetch			
N	90–175	–	200–240	110	90–172	–	200	110
P_2O_5	39–115	50	42–84	72	39–115	50	48–96	72
K_2O	18–84	50	84	72	18–84	50	96	72
Seed [kg ha^{-1}]	150–250	65–70	18–20	7–8	150–250	70–75	20–24	7–8
Pesticides[a]	1	1	3	–	1–3	2–3	3	1

[a] Number of applications.

Table 2
Details of the crop rotations implemented by eight farms investigated during period 2010–2014.

Location	Geographical coordinate	Crop 1	Crop 2	Crop 3	Crop 4
Mira	45°23′N, 12°8′W	Wheat	Maize	Soybean	–
Cona	45°12′N, 12°6′W	Maize	Soybean	Rapeseed	–
Eraclea	45°34′N, 12°40′W	Wheat	Maize	Soybean	–
Caorle	45°39′N, 12°56′W	Wheat	Maize	Soybean	Rapeseed
Mogliano	45°32′N, 12°14′W	Wheat	Maize	Soybean	Rapeseed
Ceregnano	45°2′N, 11°53′W	Wheat	Maize	Soybean	Rapeseed
Pettorazza	45°7′N, 12°1′W	Wheat	Maize	–	–
Villadose	45°4′N, 11°52′W	Wheat	Soybean	–	–

Table 3
Main climate statistics and soil physicochemical properties at the eight farms investigated during the period 2010–2014.

Location	Avg. annual daily max. temperature [°C]	Avg. annual daily in. temperature [°C]	Avg. annual precipitation [mm]	Soil texture [–]	SOM [%] [g cm^{-3}]	CEC [meq 100 g^{-1}]	Bulk Density
Mira	18.51	8.04	895	Silt-loam	1.76	14.07	1.41
Cona	18.40	9.07	770	Loam	5.34	26.62	1.43
Eraclea	18.28	8.44	891	Silt-loam	2.84	18.84	1.41
Caorle	18.25	8.26	939	Silt-loam	1.63	9.74	1.41
Mogliano	18.51	8.96	943	Clay-loam	1.77	25.23	1.32
Ceregnano	19.00	8.31	750	Loam	1.75	25.87	1.42
Pettorazza	19.00	8.31	749	Sandy-loam	2.37	21.10	1.42
Villadose	19.00	8.31	750	Clay-loam	8.27	34.30	1.41

Table 4
Energy requirement and CO_2 emissions for the different production inputs used in the eight farms investigated during the period 2010–2014 (Adapted from West and Post, 2002).

Operation	Energy requirement [MJ kg^{-1}]	Carbon emission [kg C kg^{-1}]
Planting		
Maize (*Zea mais* L.)	53.36	1.05
Soybean (*Glycine* max L.)	12.86	0.25
Wheat (*Triticum aestivum* L.)	5.57	0.11
Rapeseed (*Brassica napus*, L.)	9.76	0.17
Barley (*Hordeum vulgare* L.)	5.57	0.11
Gasoline	50.23	3.106
Fertilizer		
N	57.46	857.54
P_2O_5	7.03	165.09
K_2O	6.85	120.28
Pesticides		
Herbicide	266.56	4702.38
Insecticide	284.82	4931.93
Fungicide	288.88	5177.52

2.4. Model calibration, validation and mid-term scenarios

The first step of the simulation entailed model calibration in which information on site latitude, observed weather statistics and soil profile characteristics are provided to the model. The model was calibrated against measurements of grain yield, initial SOC, and soil N content collected in both CT and NT treatments at four of the eight farms in the study (table 3). The model was validated against field measurements taken in both types of treatment. Simulations reflected the timing and type of farming operations implemented in the investigated farms. Monthly mean values for the period 2007–2011 were collected from eight meteorological stations and used as input data for the MarkSim model.

The mid-term effects of CT and NT were evaluated running a 15-year (2010–2025) wheat-soybean-maize-rapeseed crop rotation at each farm under both tillage regimes. Climate data for the period 2010–2025 were generated using MarkSim (Jones and Thornton, 2000), a daily weather generator developed to simulate weather time series from measured monthly climate data. The MarkSim model requires site-specific input databases of past records to generate future observation. The software generates the most plausible daily weather data applying different atmospheric general circulation models (GCMs) and interpolates the data using a cell grid of 5 × 5′ (longitude x latitude). Daily weather data for the simulation period (2010–2025) were calculated aver-

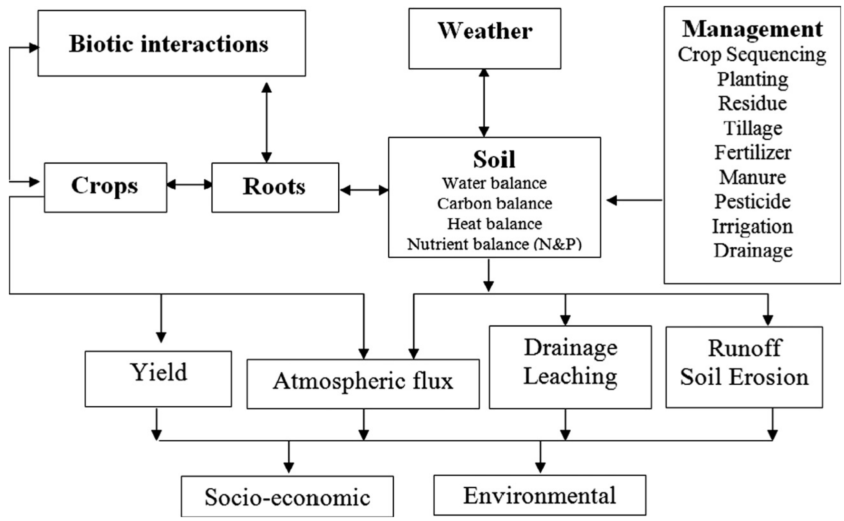

Fig. 1. Schematic representation of the main subcomponents of the SALUS soil-crop model (Basso and Ritchie, 2015).

Table 5
GCMs available in the MarkSim model considered to generate SALUS climatic inputs (Adapted from Jones and Thornton, 2000).

GCM	Reference	Source
BCCR-BCM 2.0	Bjerknes Centre for Climate Research (University of Bergen, Norway)	Furevik et al. (2003)
CNRM-CM 3	Meteo-France/Centre National de Recherchers Meteorologiques (France)	Déqué et al. (1994)
CSIRO-Mk 3.5	Commonwealth Scientific and Industrial Research Organisation Atmospheric Research (Australia)	Gordon et al. (2002)
ECHam 5	Max Planck Institute for Meteorology(Germany)	Roeckner et al. (2003)
INM-CM 3.0	Institute for Numerical Mathematics (Moscow, Russia)	Diansky and Volodin (2002)
MIROC 3.2(medres)	Centre for Climate System Research (CSSR), National Institute for Environmental Studies (NIES), Frontier Research Centre for Global Change (FRCGC) (University of Tokyo, Japan)	K-1 Model (2004)

aging the six GCMs reported in Table 5. Simulations were performed using an atmospheric CO_2 value of 405 ppm in accordance to the A1B scenario described in the 5th IPCC Assessment Report (2013).

3. Results and discussions

3.1. SALUS model validation

The model demonstrated a high level of reliability in simulating grain yields (Fig. 2). Values of root mean square error (RMSE) across treatments averaged 0.70 t ha^{-1}, a relative RMSE (RRMSE) of 12%, a normalized deviation (ND) of 0.005 and a global efficiency (EF) of 0.96. The high model goodness of fit can be appreciated considering that |ND| and EF values commonly reported in modelling exercises are >0.5 and <0.1, respectively (Dumont et al. 2012).

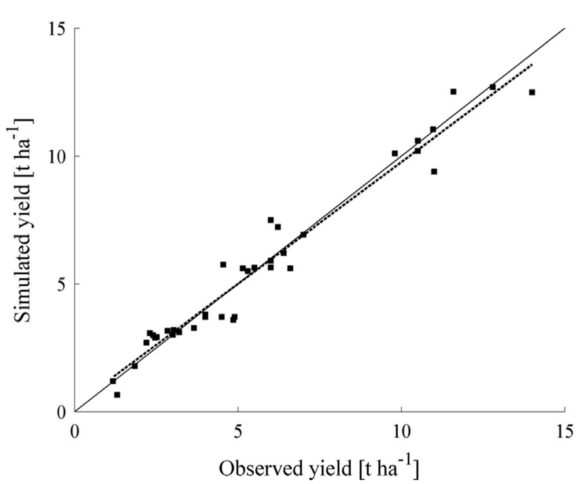

Fig. 2. Simulated vs observed yields (expressed as dry matter) for wheat, soybean, maize and rapeseed crops at the eight farms investigated using the SALUS model.

Average RMSE and RRMSE for SOC simulations were 4.37 t ha^{-1} and 11.9%, respectively, while respective mean values for ND and EF were 0.02 and −0.17. The negative EF value was due to the lower rate of SOC increase simulated by the model when compared to observed values as well as the relatively small data set (Fig. 3). At some sites (*e.g.* Caorle) the model tended to underestimate SOC increments in the NT regime. However, SOC dynamics averaged across the eight farms were in good agreement with observations (Fig. 3).

3.2. Long-term evolution of soil organic carbon

Model simulations highlighted a decrease in SOC under both management regimes and for both soil depths investigated (Fig. 4). Starting from an average initial content of 38.2 t ha^{-1}, final SOC values after 15 years reached 19.8 t ha^{-1} (−48%) for CT, and 33.6 t ha^{-1} (−12%) for NT. The greater oxidation rates that led to higher SOC losses in CT were attributed to tillage practices and the lack of cover crops. Same tendencies were observed for the second soil layer (15–26 cm), with respectively −48% and −15% under CT and NT. Similar results were reported by Senthilkumar et al. (2009), Bertocco et al. (2008) and So et al. (2001) in the US, Italy, and Australia.

Each set of SOC temporal series were fitted using the following exponential decay model (Fig. 5A and B):

$$SOC(t) = SOC_0 \cdot e^{-\lambda t} \tag{1}$$

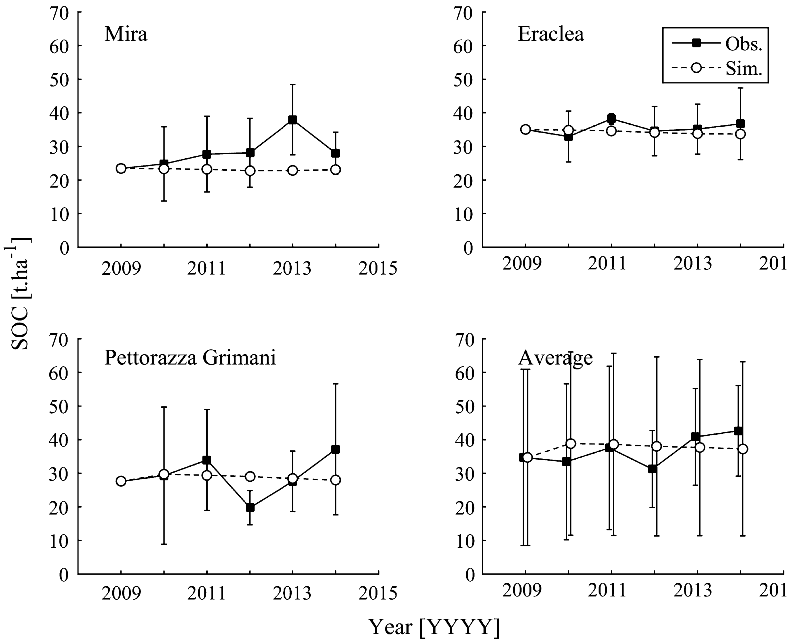

Fig. 3. Simulated vs observed SOC content in the top soil (0–15 cm) under NT regime for three sample farms and the average of the eight farms. Solid black squares (■) indicate observations, empty circles (o) indicate simulated values. Bars represent standard errors. The three sites were selected as the respective datasets included at least three repetitions for each SOC measurements.

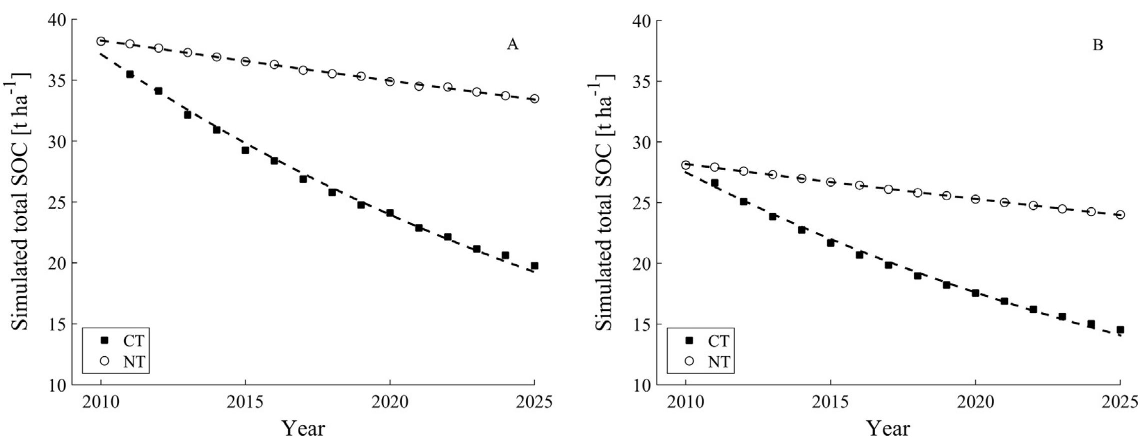

Fig. 4. Evolution of average SOC content in the 0–15 (A) and 15–26 cm (B) soil layers over 15 years (2010–2025) under CT (■) and NT (o) regimes. Values represent averages across the eight farms investigated.

The correlation coefficient of the fitting exceeded 0.99 for both CT and NT simulated SOC values. The analysis of λ values highlighted that it would take approximately 16 years of continued CT regime to halve initial SOC stocks, while the same level of SOC depletion would take about 77 years under NT in the upper 0–15 cm soil layer. SOC oxidation rates under NT are therefore almost 5 times slower than under CT, indicating the greater sustainability of NT practices compared to CT. Regarding the soil layer 0–26 cm, the ratio was close to 4, with λ equaling 15.5 and 64 respectively for CT and NT.

Variations in SOC content (relative ΔSOC) during the 2010–2025 period were assessed at four-year intervals to determine the impact of CT and NT practices during the duration of one crop rotation (wheat-soybean-maize-rapeseed). SOC content decreases under CT varied between 2.7% and 3.9% per rotation, with a tendency to decrease less over time (Fig. 5A) in the upper soil layer. Similar results were observed for the 15–26 cm soil layer (Fig. 5B). On the contrary, relative ΔSOC variations under NT were smaller and on average resulted in a 0.7% decrease at each crop rotation (Fig. 5A and B).

SOC evolution under the two tillage regimes was further analyzed by comparing the relative ΔSOC losses for each farm against the initial soil organic matter content (Fig. 6). Lowest initial SOM content led to the smallest losses in SOC over the simulated period. Highest SOC loss rates were simulated for the soil at Villadose (Table 3), which had the highest initial SOM content of 8.27%. Corresponding SOC losses equaled -64 t ha^{-1} (ΔSOC = -67%) under CT and -16 t ha^{-1} (ΔSOC = -16%) under NT in the upper soil layer (0–15 cm). Higher variability in the results were observed for the 15–26 cm soil layer, but tendencies remained the same (Fig. 6B).

Linear regressions were fitted to the CT and NT datasets and the ratio between the slopes of the two curves equaled 3.6 in the upper soil layer (0–15 cm). This indicates that, at equal initial SOM content, soils under CT management would lose almost four times the C lost under NT management. This ratio equaled 5.45 for the 15–26 cm soil layer, with lower ΔSOC values but with a lower

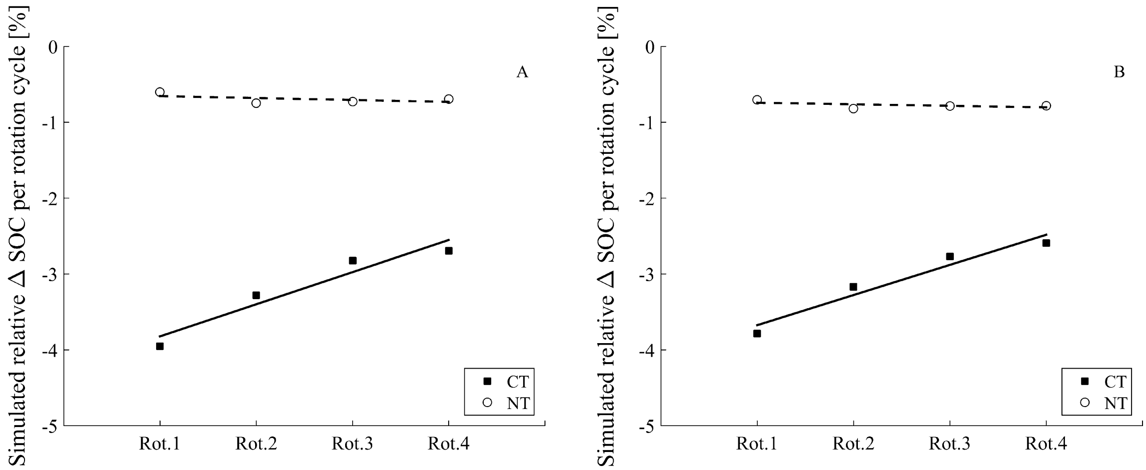

Fig. 5. Relative SOC variations calculated at four-year increments (equivalent to the duration of one crop rotation) under CT (■) and NT (o) regimes. SOC values refer to the top soil 0–15 cm (A) and 15–26 cm (B).

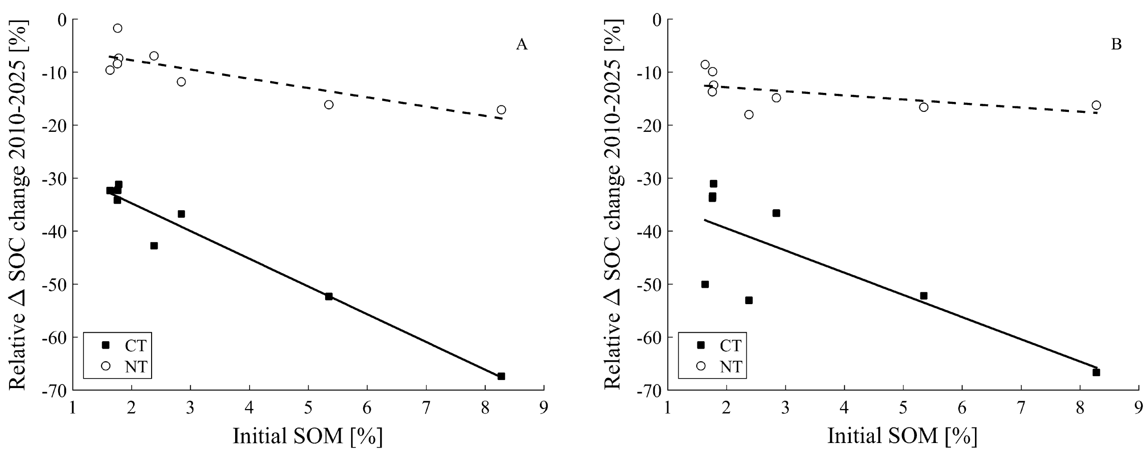

Fig. 6. Simulated relative ΔSOC variations (A: 0–15 cm; B: 15–26 cm) during the period 2010–2025 under CT (■) and NT (o) regimes as a function of the initial soil organic matter (SOM) content. Values represent the variations simulated for each of the eight farms investigated.

slope observed for NT sites (Fig. 6B). Similar results were reported by Senthilkumar et al. (2009), who compared the slopes of ΔSOC curves under CT and NT regimes during a simulated 18-year period and found that SOC evolution patterns in agricultural soils are greatly impacted by both tillage regimes and the initial SOM content.

3.3. CO_2 emissions due to farming operations

Fertilizer production and application were the most important sources of CO_2 emissions (39%) per area of cultivated land under both CT and NT regimes (Table 6). Lower values were reported for the drying of harvested yields (23–26%), mechanization (14–21%) and planting (13–23%). Average CO_2 emissions due to mechanization were 49% lower under NT than CT (197 kg ha^{-1} vs 338 kg ha^{-1}). Emissions savings were attributed to the lower number of passes required under NT and the higher working capacity of machinery used in the NT. On the other hand, planting activities under NT contributed more CO_2 emissions than in CT (323 kg ha^{-1} vs 199 kg ha^{-1}). This was due to the higher seeding densities and different seeding techniques (drill) adopted in NT.

The greatest CO_2 emission reduction between NT and CT was observed in maize production (0.47 t CO_2 ha^{-1}), caused mainly by a reduction in the amount of fertilizer used (−21%). The decreased fertilization rates in NT indirectly reduced CO_2 emissions due to mechanization since the lower soil nutrient concentrations diminished weed populations, resulting in fewer hoeing operations. However, the CO_2 emission reductions due to decreased cultivation and yield drying requirements in NT were largely offset by higher emissions from pesticides and planting operations.

Differences in CO_2 emissions between CT and NT were smaller in wheat, soybean and rapeseed and resulted in 0.06 t ha^{-1}, −0.06 t ha^{-1} and −0.14 t ha^{-1}, respectively. Wheat was the only crop where overall CO_2 emissions under NT were higher than in CT. This was due mainly to the impact of cover crops which returned a higher amount of C to the soil.

3.4. Overall impact of NT and CT on total CO_2 emissions

Tillage regimes had a substantial impact on SOC dynamics in relation to initial SOM conditions (see Table 7). Tillage regimes do not only affect SOC content but also SOC oxidation rates and, therefore, soil-derived CO_2 emissions.

Using model simulations, CO_2 emissions savings (ΔCO_2) were calculated as the differences between the CO_2 emissions from the soil under CT and NT regimes ($\Delta CO_2 = CO_{2,CT} - CO_{2,NT}$) (Fig. 7). In accordance with the results reported in Fig. 6, ΔCO_2 emission savings increased with the initial SOM content. Highest savings were simulated for the soil at Villadose (10.8 t ha^{-1}), while smallest

Table 6
Specific CO_2 emission factors [kg C-CO_2 ha^{-1}] for each product or farming operation during each phase of the wheat-soybean-maize-rapeseed crop rotation.

Component	Wheat		Soybean		Maize		Rapeseed		Average (%)	
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
Mechanization	318	220	323	155	369	187	343	228	338 (21%)	197 (14%)
Planting	405	538	160	247	137	339	94	168	199 (13%)	323 (23%)
Fertilizers	786	812	37	37	1037	818	625	563	621 (39%)	557 (39%)
Pesticides	9	24	15	51	14	46	4	9	11 (1%)	33 (2%)
Drying	284	270	240	223	937	630	213	172	418 (26%)	324 (23%)
TOTAL	1801	1864	774	713	2494	2020	1279	1140	1587 (100%)	1434 (100%)

Table 7
Simulated average CO_2 emission savings (ΔCO_2) under NT regime compare to CT over the 2010–2025 period for the upper soil layer (0–15 cm). CO_2 emission savings are reported as due to reduction of SOC oxidation (ΔCO_2 soil), farming operation management (ΔCO_2 mgt), annual sum of ΔCO_2 soil and mgt (Total ΔCO_2) and cumulative savings over time (Cumul. ΔCO_2).

Year	ΔCO_2 soil [t C-CO_2 ha^{-1}]	ΔCO_2 mgt. [t C-CO_2 ha^{-1}]	Total ΔCO_2 [t C-CO_2 ha^{-1}]	Cumul. ΔCO_2 [t C-CO_2 ha^{-1}]
2010	–	–	–	–
2011	6.81	−0.03	6.78	6.78
2012	3.86	0.25	4.11	10.89
2013	5.94	0.17	6.11	17.00
2014	3.08	0.09	3.17	20.17
2015	4.96	0.14	5.10	25.28
2016	2.25	0.11	2.36	27.64
2017	3.93	0.14	4.08	31.72
2018	3.22	0.26	3.48	35.19
2019	3.14	0.00	3.15	38.34
2020	0.84	0.08	0.92	39.26
2021	3.38	0.31	3.70	42.95
2022	2.57	0.12	2.68	45.64
2023	2.13	−0.03	2.11	47.74
2024	1.11	0.25	1.36	49.11
2025	2.17	0.17	2.34	51.45

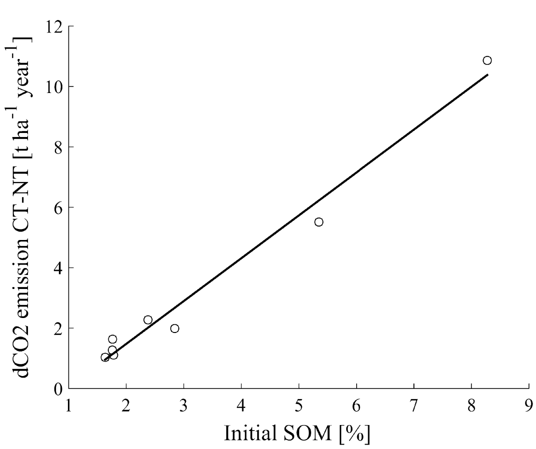

Fig. 7. Simulated CO_2 emissions savings (ΔCO_2) form soils under NT for the period 2010–2025 as a function of the initial organic matter content. Values represent the CO_2 emissions savings between CT and NT simulated for each of the eight farms investigated.

reductions in CO_2 emissions were obtained for the Caorle soil (1.0 t ha^{-1}).

Overall CO_2 emissions under CT and NT were compared to evaluate the CO_2 mitigation potential of NT practices (Fig. 7). Model simulations indicate that, over a 15-year period, an average of 51.5 t CO_2 ha^{-1} could be saved in farms in the Veneto region if NT practices were adopted at all of the farms in this study, when considering only the 0.15 cm soil layer. This value raised up to 85.7 t CO_2 ha^{-1} considering the 0–26 cm soil-layer.

4. Conclusions

The results of this study provide insight on yields, CO_2 emissions and SOC dynamics that could be valid for other temperate cereal-based cropping systems under CT or NT even though the results of this study are influenced by the soil and climate conditions of the sites evaluated.

Overall, simulations indicated that SOC stocks can decrease under both CT and NT regimes, however SOC oxidation rates were substantially lower under NT. Critically, the greatest reduction in CO_2 emission was observed when NT was adopted in soil with high levels of SOM. This highlights the benefits of NT adoption in terms of soil fertility preservation and CO_2 emissions mitigation.

Average CO_2 emissions due to mechanization and grain drying were 30% lower under NT than CT thanks to the lower number of passes required by NT practices and the higher working capacity of machinery used in the NT. However, the CO_2 emission reductions due to reduced use of equipment and yield drying requirements in NT were largely offset by higher emissions from pesticides and planting operations.

On the whole, simulations indicated that adopting NT regimes in the Veneto region could reduce CO_2 emissions by an average of 86 t C-CO_2 ha^{-1} over a 15-year period when considering the ploughing depth (0–26 cm). The results of this study will contribute to defining environmentally and agronomically sound tillage practices to reduce CO_2 emissions from agriculture and preserve soil fertility. While conducted within a single region in southern Europe, the insight into SOC dynamics and CO_2 losses provided by this study are valid for similar agroecosystems located in temperate climates.

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