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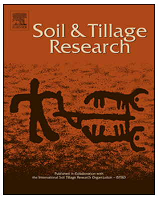

Modeling soil organic carbon and carbon dioxide emissions in different tillage systems supported by precision agriculture technologies under current climatic conditions

Donato Cillis[a], Bernardo Maestrini[b], Andrea Pezzuolo[a,*], Francesco Marinello[a], Luigi Sartori[a]

[a] *Department of Agroforesty and Landscape, University of Padua, Italy*
[b] *Department of Geological Sciences, Michigan State University, East Lansing, MI, USA*

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ABSTRACT

Soil organic matter (SOM) represents the biggest pool of carbon within the biosphere and influences the flux of greenhouse gases between land surface and atmosphere. In this regard, conservation tillage systems have been adopted to reduce negative impacts of conventional tillage practices on greenhouse gases (GHG) emissions. However, the role of these techniques to increase carbon sequestration also depends upon soil features and climatic conditions, which is studied and managed by precision agriculture (PA) principles and technologies. Simulation models have shown to be useful tools to understand the interaction between soil, climate, genotypes and management practices to simulate the long-term effects of management approaches of different soils on crop yield, soil organic carbon (SOC) storage, and GHG emissions. The research goals of this study are (1) to examine the mid-term (15 years) trajectory of SOC in the upper 0.4 m of the soil profile under different tillage systems using the SALUS model; (2) determine the impact of PA on the inputs to the crop and CO_2 emissions; (3) identify the strategies, derived from the synergy between conservation agriculture and PA, so as to decrease the CO_2 emissions of agricultural systems. The validated SALUS simulation showed a significant reduction in SOC losses in minimum tillage (MT) and no-tillage (NT), 17% and 63% respectively, compared to conventional tillage (CT). Furthermore, the adoption of conservation tillage techniques decreased carbon emissions related to farming operations, while PA technologies led to an optimization of the exhaustible sources such as fossil fuels and fertilizers. Finally, the synergy between conservation tillage systems, especially NT, and PA strategies represents a useful tool in terms of carbon emissions mitigation with a reduction of 56% of total CO_2 as compared to CT.

1. Introduction

Agricultural systems are required to satisfy the increasing global demand for food and fibre for a growing population (Boscaro et al., 2018). The intensification of the current systems in term of inputs and outputs lead to heightened concerns regarding their impact on the environment (Miller et al., 2007).

Soil organic matter (SOM) is one of the most important factors affecting agricultural production. SOM mediates nutrient cycling (Bolinder et al., 2010; Lal and Follett et al., 2009), soil aggregates, and water-holding capacity (Huntington, 2007). Therefore, SOM depletion may lead to soil degradation, which affects sustainable agricultural development and environmental health (Tang et al., 2006). Also, the carbon contained in soil organic matter (soil organic carbon, SOC) represents the biggest carbon sink and source in the biosphere, and small changes in its mineralization rate may have a large impact on greenhouse gases (GHG) emissions (Wang et al., 2015). One option to mitigate increases in GHG concentrations in the atmosphere is the biological sequestration of CO_2 (Reicosky, 1997). Biological carbon sequestration in the soil represents the net removal of CO_2 from the atmosphere into long-lived sinks, or pools, of carbon (Lal, 2008).

Management practices such as conservation tillage systems, mulching, and cover crops have shown to increase the content of C in agricultural soils (Ludwig et al., 2011; Pezzuolo et al., 2014). Each tillage technique influences differently the amount of soil carbon sequestered and the distribution of C in the soil (Alvarez, 2005). Therefore, the combination of different management practices can contribute to mitigating climate change in different ways (Marraccini et al., 2012).

Conservation tillage techniques, such as minimum tillage (MT) and no-tillage (NT), have been adopted to reduce adverse impacts of conventional tillage practices, even if sometimes characterized by lower crop yields (Van den Putte et al., 2010). Conventional tillage (CT),

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[*] Corresponding author: Department of Agroforesty and Landscape, viale dell'Università 16, 35020 Legnaro, Italy.
E-mail address: andrea.pezzuolo@unipd.it (A. Pezzuolo).

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characterized by the inversion of soil layers through ploughing leads to rapid mineralization of SOC, increases the soil erosion create a plough pan and increases energy demands for machinery (Bertolino et al., 2010; Rusu, 2014).

Over the last two decades numerous experiments supported the hypothesis that conservation tillage increases soil organic matter content (Kassam et al., 2009), however recent literature syntheses challenges the effectiveness of conservation tillage on the basis that results maybe often be biased by a lack of equalization of soil mass between tillage practices (Powlson et al., 2016) and by recognizing that not all conservation practices are equally effective in reducing carbon emissions (González-Sánchez et al., 2012).

In addition to altering the SOC levels, conservation tillage also alters its distribution in the soil profile, in fact, conservation tillage practices have shown to increase the C content in the upper soil layers whereas conventional tillage often results in an increment of SOC in the deeper soil profile, particularly near or at the bottom of the tilled layer (Angers and Eriksen-Hamel, 2008; De Sanctis et al., 2012). The potential for these techniques to increase carbon sequestration also depends upon soil features and climatic conditions (Grace et al., 2006). The acknowledgement of soil spatial variability represents the first requirement to adopt precision agriculture technologies and spatially variable practices (PA) (Mulla and Schepers, 1997). PA can be defined as the application of technologies, principles, and strategies for management of space and time variability, to increase crop performance and environmental quality (Pierce and Nowak, 1999, BasSo et al., so et al., 2001, 2007). In this regard, variable rate input (VRI) on stable homogeneous zones promote an increase in crop yield and reduce negative environmental consequences (Basso et al., 2016a). Furthermore, simulation models have shown to be useful tools to understand the interaction between soil, climate, genotypes and management over space and time and to design best management practices required for sustainable crop production (Basso and Ritchie, 2015). Simulation models are also used to simulate the long-term effects of management approaches of different soils on crop yield, SOC storage, and GHG emissions (Pezzuolo et al., 2017; Manyowa et al., 2013). In this regard, Iocola et al. (2017) tested four different simulation models to determine the effects of different soil tillage techniques on crop yield and changes in SOC stock under current and future climate scenarios.

Here we use simulation models together with measured data of energy consumption to assess the energy efficiency of different management strategies. The strategies tested in this simulation experiment include three different tillage techniques and the adoption of PA technology (automatic steering and variable inputs rate).

Considering all the issues described above, the research goals of this study are (1) to examine the mid-term (15 years) trajectory of SOC in the upper 0.4 m of the soil profile under different tillage systems using the SALUS model; (2) determine the impact of precision agriculture on managing operation's CO_2 emissions; (3) identify the strategies, derived from the synergy between conservation agriculture and precision agriculture, so as to decrease the CO_2 emissions of agricultural systems.

2. Material and Methods

2.1. Study area and climate data

This experiment was conducted at the Vallevecchia demonstration farm (45.63 °N, 12.95 °E), in the Venice Lagoon district - Italy. The study area is mainly characterized by sandy-loam soil (Molli-Gleyic Cambisols, FAO, 2001), and most of the surface is below average sea level. The farm is also affected by saltwater intrusion, a condition that leads to high spatial variability that affects crop production (De Franco et al., 2009) (Fig.1). The total study area encompasses about 18 ha, then divided into 12 plots with an area of about 1.5 ha each, obtaining four repetitions.

Yield data from the 2014-2015 and 2015-2016 growing seasons were used for the SALUS calibration and validation. The grain yields derived from 76 of the 80 total treatments were considered in the study. Because of the high number of treatments planned, not all of the observed grain yields could be attained during the first two years of experimentation. On the other hand, the SALUS model has shown a high level of reliability in simulating grain yields.

The total annual rainfall (935 mm·year^{-1}) and temperature (13.7 °C) were determined from a 23-year dataset recorded at a nearby agrometeorological station. Rainfall was distributed mostly in the Fall and the Spring, while a monthly maximum temperature of 23.8 °C in July and a minimum of 3.6 °C in January was found. In the experimentation years, the annual rainfall was 708 mm and 1076 mm for the 2015 and 2016 seasons respectively. The average annual temperature was 13.9 °C for 2015, and 13.6 °C for 2016 (Fig. 2).

2.2. Tillage systems and agronomic management

The study area was managed following the typical farming operation characterized by deep soil tillage and the inversion of the soil layers for five years before starting the experimentation. Successively, three soil tillage systems characterized by varying degrees of soil cultivation intensity were analyzed in the experimentation:

Conventional tillage (CT): the soil was ploughed down to 35 cm deep, leading to the inversion of soil layers. Soil ploughing was followed by seedbed preparation using a tine cultivator at 25 cm and power-harrow at 10 cm.

Minimum tillage (MT): the initial technique conducted with a tine cultivator at 25 cm depth without the inversion of soil layers. Seedbed preparation was carried out during planting operation using a combined power-harrow planter.

No-tillage (NT): seeds were planted without working soil surface. Seeding was conducted by planters using special discs that make a narrow trough on the soil surface for seeds deposition.

Besides, in every tillage systems crops residue is cut and uniformly distributed over the fields. In this regard, crops residue is affected by processes characterizing the different tillage systems. The experimentation did not consider organic fertilizer applications to fill the organic carbon pool but tried to reach it through managing strategies.

Consequently, each tillage system was accompanied by crop rotation including the most important crops present in the Po Valley: wheat (Triticum aestivum L.), canola (Brassica napus L.), corn (Zea mays L.) and soybean [Glycine max (L.) Merr.]. If not seeded with the main crop, the soil surface was permanently covered by sowing cover crops using conservation tillage techniques. In addition, MT and NT were integrated with PA technologies, consisting of an automatic steering guidance system, control units allowing automatic section control, and variable rate treatments (VRT). Finally, to evaluate the contribution of PA within the different conservation tillage techniques investigated, central test strips managed with fixed rates of inputs were identified (Table 1).

2.3. Study of the variability and homogeneous zones management

For the characterization of spatial variability, we collected the soil data from the homogenous zones using a stratified sampling scheme representative of the whole field. The definition of homogeneous zones at this site was previously established by analyzing the data obtained from proximal or remote sensors that provide information on soil (texture, SOM, cation exchange capacity, electrical conductivity, pH, NPK availability, sodium adsorption ratio), vegetation and yield (Cillis et al., 2017a). The study area was divided into 4 zones characterized by an increasing productive potential from A to D (Fig. 3).

Successively, the optimal seed density and nitrogen fertilization rates for the different treatments were defined based on the SALUS model simulations (Cillis et al., 2017b). Table 2 shows optimal seed and nitrogen rates of the homogeneous zones managed with different tillage