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Conservation agriculture and cover crop practices to regulate water, carbon and nitrogen cycles in the low-lying Venetian plain

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ABSTRACT

Sustainable land management (SLM) practices, aimed at balancing competitive agricultural production and environmental protection, have been encouraged throughout the EU through policy and subsidisation. Adoption of SLM practices that regulate biogeochemical cycles requires further study, especially given the effects of local pedo-climatic variability. Conservation agriculture (CA) and cover cropping (CC) as opposed to conventional agriculture (CV), were carried out in field experiments and evaluated with modelling studies in order to mitigate the loss of soil organic carbon (SOC) and water and air pollution. All experimental treatments utilised a three-year crop rotation (maize, soybean, and wheat), and crop residues remained either atop the soil surface (CA) or were incorporated with tillage operations (CC and CV). As of March 2016, 17-month recordings from three soil-water monitoring stations per treatment (9 in total) were combined with climatic data to estimate water and N fluxes in the 0–60 cm layer. Carbon fluxes were quantified considering SOC and biomass contents. The biogeochemical model DeNitrification DeComposition (DNDC) was employed to evaluate long-term (105-yr) C dynamics and quantify greenhouse gas (GHG) emissions as affected by SLM practices and climate conditions. Experimental results showed significant differences in crop production between treatments, with lower average yields in CA (5.4 Mg ha^{-1}) than in CC (7.9 Mg ha^{-1}) and CV (8.5 Mg ha^{-1}). Continuous soil cover in CA and CC determined the soil-water balance through increased evapotranspiration and reduced percolation (−30%) relative to CV. On the other hand, CC and CV tillage operations significantly affected NO_3-N concentrations, with higher soil solution concentrations in tilled (CV = 74.6 mg l^{-1}; CC = 58.1 mg l^{-1}) than in untilled (CA = 14.0 mg l^{-1}) systems. Model results emphasised that SLM practices responded differently in the short and long terms due to initial inertia to C changes and lower N_2O fluxes, followed by higher SOC sequestration, and increased N_2O emissions. These results demand time–dependent studies that weigh agro-environmental benefits provided by SLM practices against management alternatives to find a suitable compromise for stakeholders.

1. Introduction

There is growing interest in Europe to establish sustainable land management (SLM) practices that provide ecosystem services beyond maximising crop yield (Maier and Shobayashi, 2001; Van Zanten et al., 2014). The Rural Development Programme (RDP) and agri-environment schemes finance SLM practices to favour protection, conservation, and improvement of natural resources (soil, water and air), biodiversity, and rural area landscape and cultural heritage (Uthes and Matzdorf, 2013). Practices that provide continuous soil cover (e.g., cover crops) and minimal soil disturbance (e.g., reduced or no tillage) of arable lands have been supported in > 50% of RDPs at the EU27-level (Keenleyside et al., 2011; Zimmermann and Britz, 2016). It is well known that the primary function of cover crops (CC) is to tighten the nitrogen cycle, especially in the short term, by reducing nitrate leaching and by acting as a green manure (Constantin et al., 2010; Gabriel and Quemada, 2011). Nevertheless, depending on the water cycle (e.g., amount of rainfall, drainage) and period of establishment, CC may also negatively affect crop production by subtracting water and immobilising nutrients (Thorup-Kristensen et al., 2003). A secondary role of cover crops is to increase soil organic carbon (SOC) stocks, and in turn, soil fertility of croplands (Poeplau and Don, 2015), although the debate of relative effectiveness of cover crops versus other practices (e.g., minimal soil disturbance, incorporation of organic amendments) continues.

Conservation agriculture (CA) is a system of agronomic practices that minimises mechanical soil disturbance, maintains permanent soil cover by using crop residues and cover crops, and includes crop rotation

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(Farooq and Siddique, 2015). It has received wide attention as a way to reverse the decline in soil functions experienced in intensive agricultural systems, such as SOC stock depletion, microorganism habitat loss, and nutrient cycling imbalances, which make food and feed production unsustainable in the long term (Verhulst et al., 2010). Alternatively, CA can negatively or positively affect soil structure properties (e.g., bulk density, soil strength) depending on local context (Soane et al., 2012). In particular, while a change in soil hydrology is usually expected, some authors (e.g., Palm et al., 2014) found CA enhanced water infiltration from structure stability and bio-macropore connectivity (i.e., wormhole) improvements, while Lipiec et al. (2006) reported compromised water infiltration (−61%) due to high traffic soil compaction. Moreover, higher soil moisture content from crop residue mulching (Liu et al., 2013) also offsets cover crop water consumption (Thorup-Kristensen et al., 2003), which can be critical in rainfed systems.

Considering the complexity of agro-ecosystems and quantification of their services, it is not surprising that simulation models combined with field studies have been used increasingly to improve predictions of agro-environmental indicators. Models to predict GHG emission have been developed, as have biogeochemical models that integrate several management and pedo-climatic factors in sub-models (e.g., biomass production, grain and nutrients allocation, soil-water dynamics, C and N flows) in an attempt to quantify the agronomic and environmental outcomes associated with the adoption of different SLM practices (Xu et al., 2013; Cui et al., 2014).

Despite the growing attention of scientists and policymakers with economic incentives to encourage adoption of SLM practices, CC and CA use among European farmers remains weak (Basch et al., 2015; Bergtold et al., 2017). Other than direct compensation to farmers for adopting SLM practices, farmers remain uncertain of their ability to match the dual challenges of maintaining economic viability and improving environmental quality. Two reasons inform this predicament of further adoption. First, too little attention has been paid to the effect of pedo-climatic variability on SLM effectiveness to guarantee balanced ecosystem service trade-offs (Power, 2010; Primdahl et al., 2010). Second, middle and long-term effects are not fully understood and may differ from short-term outcomes (Constantin et al., 2010; Piccoli et al., 2017).

In Veneto region (northeast Italy), both conservation agriculture and cover crops were subsidised and adopted during the 2007-2013 and 2014-2020 RDPs (Regione Veneto, 2013, 2015) on an area representing about 1% of the region's arable land (Dal Ferro et al., 2016). However, with the aim to increase their implementation, CC and CA were selected as promising land management practices after a participatory process that engaged stakeholders under the EU FP7 project "RECARE – Preventing and Remediating degradation of soils in Europe through Land Care" (http://www.recare-project.eu/). The general goal of RECARE in the study area is to reverse the degradation of mineral soils of Veneto that generally have low SOC content.

By integrating experimental field results with model predictions, this study aims to evaluate the potential ecosystem services provided by conservation agriculture (CA) and cover cropping (CC) practices on SOC dynamic, atmospheric composition and climate regulation, nutrition biomass and regulating of water conditions.

2. Material and methods

2.1. Study area

The experiment was conducted on a farm located in the southwest of the low-lying Venetian plain (45° 2.908′ N, 11° 52.872′ E, 2 m a.s.l.) (Fig. 1), characterised by a water table level ranging from about −250 cm in summer to −70 cm in winter. The soil is silty-loam Endogleyc Cambisols (FAO-UNESCO, 1990) and of medium fertility due to its relatively low SOC concentration (1.2 g 100 g^{-1}) (Table 1). The subhumid climate receives an annual rainfall of 673 mm that is uniformly distributed throughout the year (129 mm in winter and 187 mm in autumn). Temperatures rise between January (−0.2 °C minimum average) and July (30.6 °C maximum average), and the 848 mm reference evapotranspiration (ET$_0$) exceeds rainfalls between May and October with a maximum in July (4.8 mm d^{-1}).

2.2. Experimental design and treatments

The field experiment established in October 2010 and still underway compares a conventional agricultural (CV) system with cover crop (CC) and conservation agriculture (CA) managements. CC and CA systems were set-up per Agri-environmental Measures 214 – Sub-Measure "i" (also called "Eco-compatible management of agricultural lands") of the Rural Development Programme for the Veneto Region during the period 2007–2013 (Regione Veneto, 2013) stemming from European Council Regulation (EC) No 1698/2005. Study lay-out consists of three rectangular adjacent plots (average size: 1.62 ha, about 540 m length × 30 m width), one for each specific treatment.

The same four-year crop rotation of winter wheat (*Triticum aestivum* L.) – oilseed rape (*Brassica napus* L.) – soybean (*Glycine* max (L.) Merr.) – maize (*Zea mays* L.) was initially used for all treatments. In 2015, the rotation was successively simplified to three years when oilseed rape cultivation was abandoned. In CA and CC, continuous soil cover was accomplished via cover crop inter-cropping with sorghum-sudangrass (*Sorghum* × *drummondii* (Nees ex Steud.) Millsp. & Chase) in the spring-summer season and winter wheat in the autumn-winter season. This last crop replaced a vetch and barley mixture (*Vicia sativa* L. and *Hordeum vulgare* L.) used during the first four experimental years. Conversely, the soil remained bare between the main CV crops.

In CV and CC systems, crop residues and cover crops acting as green manure (in CC only) were incorporated 35 cm into the soil with a multi-board plough, and their seedbeds were prepared by disk harrow to 15 cm in depth. System CA was managed with no tillage, cover crop devitalisation, direct sowing, harvesting with crop residues left on the soil surface, and cover crop sowing.

The fertiliser base dressing was applied one to two weeks before sowing in CC and CV, whereas sub-surface band fertilisation was applied to CA during sowing. All systems were side-dressed with mineral fertilisers one time in maize and two times in wheat. As specified in the protocol (Table S1), no additional fertilisation was provided to the cover crops. In winter wheat, NPK mineral fertilisation was provided at doses of 32 kg N ha^{-1}, 96 kg P-P$_2$O$_5$ ha^{-1}, and 96 kg K-K$_2$O ha^{-1}. In soybean, only phosphorus (50 kg P-P$_2$O$_5$ ha^{-1}) and potassium (50 kg K-K$_2$O ha^{-1}) were applied as mineral fertilisers. Maize received compound mineral input (32 kg N ha^{-1}, 96 kg P-P$_2$O$_5$ ha^{-1}, 96 kg K-K$_2$O ha^{-1}) followed by urea (69 kg N ha^{-1}) at sowing (1–10 April in CV and CC, 10–20 April in CA). Side dressing treatments are performed in maize as urea (115 kg N ha^{-1}) and in wheat as ammonium nitrate (50 kg N ha^{-1}) and urea (92 kg N ha^{-1}).

Pesticide applications based on crop requirements followed an integrated pest management programme and were the same for CV, CC, and CA. Prior to spring seeding, *N*-(phosphonomethyl) glycine was applied to suppress winter cover crop in CA, while mechanical shredding was utilised to suppress winter cover crop in CC. Sorghum-sudangrass was mechanically suppressed in both CC and CA practices.

2.3. Data collection

As of March 2016, nine soil-water monitoring stations were installed in the experimental fields (CV, CC, and CA with three stations each). Each monitoring station was equipped with multi-sensor probes (HD3510.2, Delta OHM, GHM GROUP, Selvazzano Dentro, IT), suction lysimeters (60 cm depth) (Soilmoisture Equipment Corp., Santa Barbara, CA, USA), and phreatic wells (350 cm depth) to study the effects of different treatments on soil-water dynamics and nitrogen