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Conservation Agriculture practices reduce the global warming potential of rainfed low N input semi-arid agriculture

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ABSTRACT

Conservation tillage and crop rotations improve soil quality. However, the impact of these practices on greenhouse gas (GHG) emissions and crop yields is not well defined, particularly in dry climates. A rainfed 2-year field-experiment was conducted to evaluate the effect of three long-term (17–18 years) tillage systems (Conventional Tillage (CT), Minimum Tillage (MT) and No Tillage (NT)) and two cropping systems (rotational wheat (*Triticum aestivum* L.) preceded by fallow, and wheat in monoculture), on nitrous oxide (N_2O) and methane (CH_4) emissions, during two field campaigns. Soil mineral N, water-filled pore space, dissolved organic carbon (C) and grain yield were measured and yield-scaled N_2O emissions, N surplus and Global Warming Potentials (GWP) were calculated. No tillage only decreased cumulative N_2O losses (compared to MT/CT) during campaign 1 (the driest campaign with least fertilizer N input), while tillage did not affect CH_4 oxidation. The GWP demonstrated that the enhancement of C stocks under NT caused this tillage management to decrease overall CO_2 equivalent emissions. Monoculture increased N_2O fluxes during campaign 2 (normal year and conventional N input) and decreased CH_4 uptake, as opposed to rotational wheat. Conversely, wheat in monoculture tended to increase soil organic C stocks and therefore resulted in a lower GWP, but differences were not statistically significant. Grain yields were strongly influenced by climatic variability. The NT and CT treatments yielded most during the dry and the normal campaign, and the yield-scaled N_2O emissions followed the same tendency. Minimum tillage was not an adequate tillage management considering the GWP and the yield-scaled N_2O emissions (which were 39% lower in NT with respect to MT). Regarding the crop effect, wheat in rotation resulted in a 32% increase in grain yield and 31% mitigation of yield-scaled N_2O emissions. Low cumulative N_2O fluxes (<250 g N_2O-N ha^{-1} campaign^{-1}) highlighted the relevance of soil organic C and CO_2 emissions from inputs and operations in rainfed semi-arid cropping systems. This study suggests that NT and crop rotation can be recommended as good agricultural practices in order to establish an optimal balance between GHGs fluxes, GWP, yield-scaled N_2O emissions and N surpluses.

1. Introduction

Agriculture contributes to 10–12% of the total global anthropogenic greenhouse gases (GHGs) (Stocker et al., 2013), through the release of nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4). The global warming potential (GWP), which is a concept that integrates the radiative properties of all GHGs, expressed as CO_2 equivalents (CO_2-eq), is very dependent on N_2O emissions from agricultural crop systems. This gas, which is a by-product of microbial processes of nitrification and denitrification, (Firestone and Davidson, 1989), is released from soils after nitrogen (N) application (through fertilizers, manures or crop residues). By contrast, in aerated soils CH_4 uptake normally reduces GWP, because the amount of CH_4 oxidized by methanotrophic microorganisms is normally higher than the amount produced by methanogenic microoganisms (Chan and Parkin, 2001). Additionally, agricultural practices that favour carbon (C) sequestration (Robertson et al., 2000) are also considered as valuable strategies to reduce the negative effect of GHG emissions associated with crop production. Therefore, agricultural management practices (e.g. tillage, fertiliza-

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tion and crop rotation) must integrate the reduction of soil GHG emissions and the increase of organic C content, while maintaining or enhancing crop yields to satisfy increasing global food demand.

Conservation agriculture, which involves crop rotations and reduced tillage (no tillage (NT) or minimum tillage (MT)), is currently common in Mediterranean climates due to its effects on preserving soil fertility and increasing the soil C sink (Kassam et al., 2012). These tillage practices often contribute to improve important abiotic parameters involved in the production and consumption of GHG from soils such as soil water content, aeration and soil organic C (SOC) (Martin-Lammerding et al., 2011; Plaza-Bonilla et al., 2014; García-Marco et al., 2016) compared to conventional tillage (CT). However, contradictory results on N_2O and CH_4 fluxes have been reported (i.e. Pelster et al., 2011; Dendooven et al., 2012; Ball et al., 1999; Yonemura et al., 2014) due to interaction of tillage with several factors, e.g. soil type, climatic conditions (which determine the prevalence of nitrification or denitrification), nitrogen (N) fertilization rate, crop residues (type and management), and the duration of experiments (van Kessel et al., 2013).

The effect of crop rotations on GHG emissions is variable depending on rainfed/irrigated conditions, composition and management of previous crop residues (Malhi and Lemke, 2007), and mineral N remaining in soil from previous cropping phases. Cereal residues (high C:N ratio) can promote soil N immobilization when they are applied without an additional source of mineral N, consequently leading to a temporary reduction of N_2O fluxes (Huang et al., 2004). However, other authors (Sarkodie-Addo et al., 2003) have observed an enhancement of denitrification losses when a mineral source is added together with high C:N ratio residues, providing an energy supply for denitrifying microorganisms. Addition of N fertiliser may also inhibit CH_4 uptake due to the interference of enzyme activity responsible for CH_4 oxidation (CH_4 monooxygenase) with NH_3 monooxygenase (Dunfield and Knowles, 1995), depending on N rate (Aronson and Helliker, 2010). Different quantities of crop residue are added to the soil under rotational wheat and wheat in monoculture systems, which can affect net N_2O and CH_4 production due to changes in soil C and N availability.

The influence of tillage and crop rotation on the stocks of SOC has been previously assessed, showing promising but contrasting results depending on management (e.g. type and duration of rotation) and experimental (e.g. depth, number of years since the beginning of the experiment) factors (Baker et al., 2007; Álvaro-Fuentes et al., 2014; Triberti et al., 2016). Thus, to identify whether conservation tillage practices (MT/NT and crop rotation) can mitigate both soil GHG emissions and net GWP is still unclear, particularly in semi-arid areas where the weight of direct N_2O losses is expected to be lower.

In rainfed semi-arid cropping systems, characterized by a high variability in the total amount and distribution of rainfall, low N input systems are being promoted in order to match N input to the expected N uptake by crops (Kimani et al., 2003; Tellez-Rio et al., 2015), which may reduce the N surplus and also N losses (van Groenigen et al., 2010). Therefore, combining Conservation Agriculture practices with adjusted N-input is expected to provide an optimum balance between GWP and crop yields in semi-arid agro-ecosystems. In this context, the main objective of this study was to evaluate the effect of three long-term tillage systems (CT, MT and NT) and two cropping systems (wheat in monoculture and wheat in a 4-year rotation with fallow as preceding crop) on N_2O and CH_4 emissions over two campaigns. Additionally, crop yield, yield-scaled N_2O losses (YSNE) and GWP were evaluated. We hypothesized that: (1) considering climatic conditions of this experiment and the low N input, low N_2O emissions would be expected in all treatments; (2) emissions of N_2O and CH_4 in winter wheat in monoculture could be higher than in the rotational winter wheat, because of a combined effect of previous crop residues and N fertilizer application; and (3) NT would reduce net GWP as a result of the reduction of CO_2-eq emissions from farm operations and the increase of C stocks (Aguilera et al., 2013a).

2. Materials and methods

2.1. Site characteristics

A two-year study was carried out at “La Canaleja” Field Station (40° 32′N, 3° 20′W, 600 m), in Alcalá de Henares (Madrid, Spain), where a long-term tillage experiment began in 1994. Tillage systems and crop rotations including legumes and fallow have been assessed since that date. The soil was a sandy-loam *Calcic Haploxeralf* (Soil Survey Staff, 2010). The main physicochemical properties of the top soil layer (0–15 cm) were: sand, 50.8%; silt, 37.7%; clay, 11.5%; $CaCO_3$, 41.6 g kg $^{-1}$; pH_{H2O}, 7.9 and EC, 121.3 μS cm^{-1}. The site has a semiarid Mediterranean climate with dry summers. The 1994–2013 mean annual temperature and rainfall for this area were 13.5 °C and 402.7 mm, respectively.

2.2. Experimental design and management

The experiment was conducted from October 2011 to October 2013. The experimental design was a three-replicated split plot, divided into three main plots assigned to the three tillage systems (NT, MT and CT) in a randomized complete block design (Guardia et al., 2016). Each of the main plots were further divided into five subplots (10 × 25 m) assigned in a completely randomized design to the phases of an annual crop rotation, involving fallow-wheat (*Triticum aestivum* L. var. Marius)-vetch (*Vicia sativa* L. var. Senda)-barley (*Hordeum vulgare* L. var. Kika), and also wheat in monoculture. In this study, we evaluated the effect of the three tillage systems mentioned above (tillage factor) and two cropping systems (cropping factor): wheat in rotation and wheat in monoculture; during two campaigns with different climatic (i.e. rainfall amount) and management conditions (i.e. rate of N fertilizer at dressing) (campaign factor): 2011/12 (campaign 1) and 2012/13 (campaign 2), resulting in eighteen subplots (3 plots × 2 subplots × 3 replicate blocks).

Moldboard (20 cm depth) and chisel ploughs (15 cm depth) were used in autumn (early-November 2011 and late-October 2012, for campaign 1 and 2, respectively) in CT and MT plots, respectively. Then, a cultivator pass was carried out for both tillage systems. Thus, crop residues were almost completely incorporated into the soil in CT, whereas under MT the previous season's crop residues covered approximately 30% of the plot surface. No tillage involved direct drilling and spraying with glyphosate (at a rate of 2 L ha^{-1} of Sting Monsanto ®) for weed control, and previous season's crop residues were retained on the soil surface. Different types of crop residues were applied to the soil in the rotation treatment, depending on the phase of the rotation. Since wheat was preceded by fallow, the relatively small amount of biomass generated during that phase was left or incorporated into the soil surface of the following crop, winter wheat. By contrast, in wheat in monoculture, straw residue provided a greater N and C input (235 Mg C ha^{-1}; 20 kg N ha^{-1}) to the following crop of wheat. Rotational and monoculture wheat were sown on 26th November 2011 and 14th November 2012 in campaigns 1 and 2, respectively, with 210 kg seed ha^{-1}. Fertilizer was applied at seeding (16 kg N ha^{-1} as NPK, 8-24-8) in both campaigns and at dressing as ammonium nitrate (NH_4NO_3, 27-0-0) on 22nd March 2012 and 11th March 2013. The N fertilization rate at dressing was calculated by taking into account the expected crop yield and soil mineral N content two weeks before fertilizer application (February). There was a higher than average nitrate ($NO_3{}^-$-N) content in the 0–15 cm soil