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Tillage and nitrogen fertilization effects on nitrous oxide yield-scaled emissions in a rainfed Mediterranean area

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ABSTRACT

There is a strong need to identify the combination of tillage and N fertilization practices that reduce the amount of nitrous oxide (N_2O) emissions while maintaining crop productivity in dryland Mediterranean areas. We measured the fluxes of N_2O in two field experiments with 3 and 15 years since their establishment. In the long-term experiment, two types of tillage (NT, no-tillage, and CT, conventional intensive tillage) and three mineral N fertilization rates (0, 60 and 120 kg N ha^{-1}) were compared. In the short-term experiment, the same tillage systems (CT and NT) and three N fertilization doses (0, 75 and 150 kg N ha^{-1}) and two types of fertilizers (mineral N and organic N with pig slurry) were compared. N_2O emissions, water-filled pore space, soil mineral N content, grain yields, N-biomass inputs and soil total nitrogen (STN) stocks were quantified and the N_2O yield-scaled ratio as kg of CO_2 equivalents per kg of grain produced was calculated. In both experiments tillage treatments significantly affected the dynamics of N_2O fluxes. Cumulative losses of N as N_2O were similar between tillage treatments in the long-term field experiment. Contrarily, although not significant, cumulative N losses were about 35% greater under NT than CT in the short-term experiment. NT significantly increased the production of grain and the inputs of N to the soil as above-ground biomass in both experiments. Averaged across fertilizer treatments, CT emitted 0.362 and 0.104 kg CO_2 equiv. kg grain^{-1} in the long-term and the short-term experiment, respectively, significantly more than NT that emitted 0.033 and 0.056 kg CO_2 equiv. kg grain^{-1}, respectively. Nitrogen fertilization rates did not affect the average N_2O fluxes or the total N losses during the period of gas measurement in the long-term experiment. Contrarily, in the short-term experiment, N_2O emissions increased with application rate for both mineral and organic fertilizers. The use of pig slurry increased grain production when compared with the mineral N treatment, thus reducing the yield-scaled emissions of N_2O by 44%. Our results showed that in rainfed Mediterranean agroecosystems, the use of NT and pig slurry are effective means of yield-scaled N_2O emissions reduction.

1. Introduction

Human activities impact the N cycle through the production and use of fertilizers and fossil fuel combustion (Galloway et al., 2004). Agricultural and natural N inputs to the biosphere from N fertilizers, animal manure, biological N_2 fixation and atmospheric N deposition increased from 155 to 345 Tg N year^{-1} between 1900 and 2000 (Bouwman et al., 2013). That increase entails major losses of N from the agricultural systems such as nitrate leaching, erosion and gaseous emissions by denitrification. Among them, denitrification is the major terrestrial N removal process (Bouwman et al., 2013; Seitzinger et al., 2006).

The emission of N to the atmosphere as nitrous oxide (N_2O) has received recent attention due to its role as a powerful greenhouse gas (GHG) with a global warming potential (GWP) 298 times greater than the carbon dioxide (CO_2) (Forster et al., 2007) and its involvement in the depletion of the ozone (O_3) layer in the stratosphere that could result in harmful effects due to solar ultraviolet radiation (Crutzen, 1974). The transformation of N to N_2O has been related mainly to two biological processes, i.e. the loss of N as N_2O during the nitrification of NH_4^+ under aerobic conditions, and the reduction of NO_3^- under anaerobic conditions. Together,

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these processes account for 70% of global N_2O emissions (Braker and Conrad, 2011). Other processes such as chemodenitrification, chemical decomposition of hydroxylamine, nitrifier-denitrification and coupled nitrification–denitrification may also be involved in the production of N_2O, but their contribution is considered to be relatively small (Bremner, 1997; Butterbach-Bahl et al., 2013).

The production of N_2O in soils is affected by the presence of readily available C fractions such as water-soluble organic C (Burford and Bremner, 1975), oxygen availability (Linn and Doran, 1984), temperature (Saad and Conrad, 1993), pH (Bandibas et al., 1994), and the supply of ammonium and nitrate (Firestone and Davidson, 1989; Smith et al., 1997). As a result, it is easy to understand that any agricultural practice that causes changes in the soil N substrates or soil environmental conditions can lead to important variations in soil N_2O production.

Mineral N availability is a key process controlling soil N_2O fluxes. Bouwman et al. (2002) carried out a meta-analysis on 139 N_2O studies conducted in agricultural fields and observed an increase of N_2O emissions with increasing N application rates, mainly with application rates above 100 kg N ha^{-1}. Those results are also supported by the findings of Rees et al. (2013) who synthesized different European agricultural experiments. Earlier studies showed a greater amount of N_2O lost to the atmosphere when agricultural soils were manured than when mineral N fertilizers were used (Bouwman, 1990). However, other authors have obtained no differences between organic and mineral fertilizers (Meijide et al., 2009) or higher N_2O emissions when using mineral products (Meijide et al., 2007; Aguilera et al., 2013). Moreover, different results arise when separating between organic solid and liquid fertilizers (Aguilera et al., 2013). In their meta-analysis, the last authors found that only organic solid fertilizers led to significantly lower N_2O emissions than mineral fertilizers (Aguilera et al., 2013). Although in recent years several publications have covered the effect of fertilization on N_2O emission, much less attention has been paid to the interaction of different tillage and fertilization practices.

The use of conservation tillage practices has been claimed as a mechanism to reduce the CO_2 atmospheric pool by increasing the amount of organic carbon in the soil (Follett, 2001). Indeed, several studies have shown the benefits in terms of soil organic carbon sequestration when using no-tillage (NT) over a broad range of edaphoclimatic conditions (Follett, 2001). However, different authors have also suggested that the benefits obtained with the use of NT could be counterbalanced by an increase in N_2O emissions due to the greater amount of water in the soil and soluble forms of C in non-tilled systems (Aulakh et al., 1984; Ball et al., 1999; Smith et al., 2001). Nevertheless, Six et al. (2004) suggested that the emissions of N_2O could be reduced when maintaining NT over time. According to this last observation, Van Kessel et al. (2013) conducted a meta-analysis on 239 direct comparisons between conventional tillage (CT) and NT and reduced tillage (RT) and pointed out that, on average, both NT and RT did not show greater N_2O emissions when compared with CT. However, they found a significant reduction in these emissions in long-term experiments (>10 years) under NT and RT practices, mainly in dry climates.

In some areas of semiarid Spain, a large livestock intensive farming sector is a relevant economic activity, resulting in high availability of manure. The application of organic fertilizers as amendments is a valuable resource for low-fertility soils and could lead to the increase in the amount of soil organic C and N (Hernández et al., 2013). In the Mediterranean area the use of RT or NT systems is increasingly adopted due to its agricultural and environmental benefits (Kassam et al., 2012). For instance, a better crop performance under NT due to greater soil water availability has been reported (Cantero-Martínez et al., 2003; Giambalvo et al., 2012). However, the interaction between the C input concomitant with the application of organic fertilizers and the greater amount of water stored in the soil usually found under NT in the Mediterranean agricultural systems could enhance the emission of N_2O to the atmosphere (Smith et al., 2001).

Table 1
General site and soil characteristics in the 0- to 30-cm soil depth at the beginning of the experiments at the two study sites.

Site and soil characteristic	Long-term experiment	Short-term experiment
Year of establishment	1996	2010
Latitude	41°48′36″ N	41°54′12″ N
Longitude	1°07′06″ E	0°30′15″ W
Elevation (m)	330	395
Annual precipitation (mm)	430	327
Mean annual air temperature (°C)	13.8	13.4
Annual ETo (mm)	855	1197
Soil classification[a]	Typic xerofluvent	Typic calcixerept
pH (H_2O, 1:2.5)	8.5	8.0
$EC_{1,5}$ (dS m^{-1})	0.15	1.04
Organic C (g kg^{-1})	7.6	15.6
Organic N (g kg^{-1})	–	1.4
Particle size distribution (%)		
Sand (2000–50 μm)	46.5	6.2
Silt (50–2 μm)	41.7	63.3
Clay (<2 μm)	11.8	30.5

[a] According to the USDA classification (Soil Survey Staff, 1994).

The objective of our study was to identify the optimum combination of tillage and N fertilization practices to reduce the amount of N_2O emitted from the soil to the atmosphere per unit of production in dryland Mediterranean areas. Our main hypotheses were that (i) due to the higher conservation of water under NT the emission of N_2O under this tillage system would be higher when compared with CT, (ii) the greater emissions under NT are compensated by a greater yield, and (iii) the combination of organic fertilizers and NT would increase the N emitted as N_2O due to the presence of labile C in the composition of the organic materials.

2. Materials and methods

2.1. Experimental sites

The study was carried out in two experimental fields with different tillage and fertilization management established in 1996 (long-term experiment) and 2010 (short-term experiment) in northeastern Spain. Selected site characteristics and soil properties for both experiments are detailed in Table 1.

In the long-term experiment, two types of tillage (NT, no-tillage, and CT, conventional intensive tillage) and three N fertilization rates (0, 60 and 120 kg N ha^{-1}) were compared. The CT treatment consisted of one pass of moldboard plow to 25 cm depth followed by two passes of a cultivator to 15 cm depth, both in September–October. Nitrogen fertilizer was applied manually and split into two applications: one-third of the rate before seeding as ammonium sulphate (21% N) and the rest at the beginning of tillering, in February, as ammonium nitrate (33.5% N). The cropping system consisted of continuous barley (*Hordeum vulgare* L., cv. Hispanic from 1996 to 2010 and cv. Cierzo from 2010 to 2013). The historical management of the field prior to the establishment of the experiment was based on conventional intensive tillage with moldboard plowing and winter cereal monoculture.

In the short-term experiment, two tillage systems (CT with disk plow and NT), three N fertilization doses (0, 75 and 150 kg N ha^{-1}) and two types of N fertilizers (mineral N with ammonium sulphate and ammonium nitrate and organic N with pig slurry) were compared. In 2011, the CT treatment was carried out with two passes of chisel instead of disk plow due to the dry conditions of the soil. The treatment with 150 kg mineral N ha^{-1} was split into two manual applications, half of the dose before tillage as ammonium