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Soil management effects on greenhouse gases production at the macroaggregate scale

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ABSTRACT

Agricultural management practices play an important role in greenhouse gases (GHG) emissions due to their impact on the soil microenvironment. In this study, two experiments were performed to investigate the influence of tillage and N fertilization on GHG production at the macroaggregate scale. In the first experiment, soil macroaggregates collected from a field experiment comparing various soil management systems (CT, conventional tillage; NT, no-tillage) and N fertilization types (a control treatment without N and mineral N and organic N with pig slurry treatments both at 150 kg N ha^{-1}) were incubated for 35 days. Methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) production was quantified at regular time intervals by gas chromatography. In the second experiment, the effects of fertilization type and soil moisture on the relative importance of nitrification and denitrification processes in N_2O emission from soil macroaggregates were quantified. Nitrate ammonium, macroaggregate-C concentration, macroaggregate water-stability, microbial biomass-C and N (MBC and MBN, respectively) and water-soluble C (WSC) were determined. While NT macroaggregates showed methanotrophic activity, CT macroaggregates acted as net CH_4 producers. However, no significant differences were found between tillage systems on the fluxes and cumulative emissions of CO_2 and N_2O. Greatest cumulative CO_2 emissions, macroaggregate-C concentration and WSC were found in the organic N fertilization treatment and the lowest in the control treatment. Moreover, a tillage and N fertilization interactive effect was found in macroaggregate CO_2 production: while the different types of N fertilizers had no effects on the emission of CO_2 in the NT macroaggregates, a greater CO_2 production in the CT macroaggregates was observed for the organic fertilization treatment compared with the mineral and control treatments. The highest N_2O losses due to nitrification were found in the mineral N treatment while denitrification was the main factor affecting N_2O losses in the organic N treatment. Our results suggest that agricultural management practices such as tillage and N fertilization regulate GHG production in macroaggregates through changes in the proportion of C and N substrates and in microbial activity.

1. Introduction

The production and consumption of soil greenhouse gases (GHG) is mediated by several microbial processes (Conrad, 1996). For instance, soil carbon dioxide (CO_2) emissions are the result of microbial heterotrophic respiration while methane (CH_4) is normally oxidized by methanotrophic bacteria in aerobic soils (Goulding et al., 1995). Furthermore, soil nitrous oxide (N_2O) production is the result of nitrification and denitrification processes (Blackmer et al., 1980; Firestone et al., 1980; Poth and Focht, 1985). Those microbial processes are regulated by the physical protective capacity of aggregates that limit decomposition of organic C and N compounds (Elliott, 1986). Soil aggregates not only protect C and N, but they also regulate both the structure and the activity of the soil microbial community (Gupta and Germida, 1988; Miller et al., 2009). The intra-aggregate distribution of pores plays a major role in microbial access to oxygen, substrates and water. As Young and Ritz (2000) pointed out, soil structure regulates oxygen diffusion to habitat sites, depending on the connectivity and tortuosity of pore pathways. The aggregate architecture also controls the distribution of water films within soil matrix, affecting microbial microhabitats. Thus, the diffusion of oxygen to the center of

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aggregates will depend on the spatial arrangement of water films (Young and Ritz, 2000). The last factors affect the importance of denitrification and respiration activities and demonstrate the role played by soil aggregates regulating them (Beare et al., 1994; Estavillo et al., 2002). Moreover, due to their physical protective capacity, soil aggregates also regulate the microbial accessibility to substrates.

In a recent experiment, Lenka and Lal (2013) have suggested that the aggregate hierarchy theory of Tisdall and Oades (1982) could be extended to describe the effect of soil aggregation on GHG emission from soil. That theory postulates that the nature of the organic binding agents (transient, temporary and persistent) regulates different hierarchical stages of aggregation. Microaggregates are formed by the joining of primary particles and silt-sized aggregates and persistent organic binding agents, while these microaggregates are bound together into macroaggregates by temporary and transient organic binding agents. These organic materials are protected by the heterogeneity of the soil microenvironment which limits the access of decomposers and their enzymes (Shmidt et al., 2011; Ananyeva et al., 2013).

The agricultural practices play an important role in GHG emissions due to their effects on the soil microenvironment. Tillage breaks soil aggregates leading to enhanced organic matter decomposition (Álvaro-Fuentes et al., 2008; Beare et al., 1994) and reduced C and N concentration (Plaza-Bonilla et al., 2010). Contrarily, the use and maintenance of no-tillage (NT) increases the stability of soil macroaggregates (Plaza-Bonilla et al., 2013b), a fact that could lead to a reduction in heterotrophic respiration due to a greater substrate protection, thus limiting the emissions of CO_2. Likewise, CH_4 production is also affected by tillage management. For instance, in a wheat-fallow rotation, Kessavalou et al. (1998) reported higher CH4 uptake rates under NT when compared with a plough treatment. Also, Hütsch (1998a) reported 4.5–11 times greater CH4 oxidation rates under NT than under conventional tillage (CT). Ball et al. (1999) hypothesized that the reduction in CH4 oxidation usually found when tillage is performed could be due to the disturbance of the methanotrophic microbes by tillage, the changes in gas diffusivity or a long-term damage to methanotrophs due to disruption of soil structure. Tillage also has an impact on N_2O emissions. Estavillo et al. (2002), studying the effects of ploughing a permanent pasture on the emissions of this gas, observed an increase in both soil organic N mineralization and N_2O production rates from nitrification and denitrification processes after the breakage of soil aggregates by tillage.

Nitrogen fertilization has a strong impact on soil aggregation and C and N protection. The application of organic fertilizers such as pig slurry enhances the proportion of easily-decomposable C fractions (Morvan and Nicolardot, 2009) that could act as substrates for the denitrification process and the concomitant soil N_2O emissions to the atmosphere (Burford and Bremner, 1975). Sexstone et al. (1985) quantified the diffusion of oxygen within soil aggregates establishing a relationship between their size and their potential to act as denitrifying microsites within soil. Nitrogen fertilization also plays a major role in methane oxidation. Different authors (Hütsch et al., 1993; Mosier et al., 1991; Steudler et al., 1989), working with incubated soil cores from agricultural, grassland and forest experiments, observed a decrease in CH_4 uptake when applying inorganic N to soil. Contrarily, recent findings suggest that ammonium-based fertilizers could stimulate the activity of methanotrophs (Bodelier and Laanbroek, 2004).

In recent years, different experiments have been performed to analyze the effects of aggregate size on CO_2, CH_4 and N_2O production (Diba et al., 2011; Drury et al., 2004; Kimura et al., 2012). However, inconsistent results have been observed in the literature due to the simultaneous diverse microbial processes that soil aggregates can hold (Sey et al., 2008). For instance, Parkin (1987) related the spatial heterogeneity in the N_2O emissions usually observed in most experiments with the presence of particulate organic matter within soil aggregates. Those studies demonstrate that different aggregate attributes such as size or C fractions within them regulate GHG production processes. However, few experiments have studied the effects of agricultural management practices on soil GHG production at the aggregate scale.

Thus, the objectives of this study were: (i) to analyze the effect of the use of different types of tillage and N fertilization on the production of GHG by soil macroaggregates and, (ii) to quantify the relative importance of the nitrification and denitrification processes on the macroaggregate emissions of N_2O depending on the type of fertilizer used. We hypothesized that (i) CT macroaggregates would emit a greater amount of GHG due to their lower protection of the organic C and N compounds when compared to NT macroaggregates and (ii) the application of pig slurry and mineral N would result in different rates of GHG production provided by soil macroaggregates.

2. Materials and methods

Soil samples were collected from an experimental field established in 2010 in Senés de Alcubierre, NE Spain (41° 54′ 12″ N, 0° 30′ 15″ W), in an area with a temperate continental Mediterranean climate. This field experiment has a randomized block design with three replications comparing different tillage systems and N fertilization treatments. Two tillage systems (CT, conventional tillage with disk ploughing and NT, no-tillage) and two types of N fertilizers (mineral N with ammonium nitrate and ammonium sulphate and organic N with pig slurry), with three N doses (0, 75 and 150 kg N ha^{-1}), were compared. Each year, in the CT treatment, tillage is performed right before the seeding of barley (*Hordeum vulgare* L.) with one pass of a disk plough to 20 cm depth in October, after the application of organic and mineral fertilizers. The NT treatment consisted of a total herbicide application (1.5 L 36% glyphosate per hectare) for controlling weeds before sowing. Mineral N fertilizer was manually applied. The treatment with 150 kg N ha^{-1} was split into two applications: half of the dose before tillage as ammonium sulphate (21% N) and the other half at the beginning of tillering, in February, as ammonium nitrate (33.5% N). For the 75 kg N ha^{-1} treatment the entire dose was applied at tillering as ammonium nitrate. Equally, in the treatments with organic fertilization, the 75 kg N ha^{-1} rate was applied entirely at tillering and the 150 kg N ha^{-1} one was split into two applications, one half before tillage and the other half at tillering. The organic fertilization treatment consisted of the application of pig (*Sus scrofa*) slurry from a commercial farm in the area. The slurry was conventionally surface-spread using a commercial vacuum tanker fitted with a splashplate. The machinery was previously calibrated to apply the precise dose after analyzing the pig slurry. The main edaphoclimatic characteristics of the experimental site are listed in Table 1. Prior to the establishment of the experiment the field was conventionally tilled and fertilized with mineral N for four decades until 2008. Then, the whole field was transformed to no-tillage. Finally, as commented before, when the experiment started in 2010, the CT plots were added. The cropping system is a continuous barley monoculture.

2.1. Experiment 1: GHG production from soil macroaggregates under different tillage and N fertilization treatments

Soil samples were obtained from both tillage treatments (CT and NT) and the lower (0 kg N ha^{-1}, Control) and the higher (150 kg mineral N ha^{-1}, Mineral, and 150 kg organic N ha^{-} with pig