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Soil CO_2 fluxes following tillage and rainfall events in a semiarid Mediterranean agroecosystem: Effects of tillage systems and nitrogen fertilization

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ABSTRACT

The response of soil CO_2 flux to tillage operations and rainfall events was studied under semiarid Mediterranean conditions. The study was conducted on a barley monoculture agro-ecosystem during summer/autumn fallow periods in four consecutive years (2005–2008). The study compared three N fertilization levels (zero, medium; 60 kg N ha^{-1}; high, 120 kg N ha^{-1}) under three tillage systems (NT, no-tillage; MT, minimum tillage; CT, conventional tillage). Tillage operations led to a pulse of soil CO_2 flux. This pulse was linearly related to soil CO_2 flux on the day before tillage operations under MT (slope = 4.22) and CT (slope = 16.7), indicating the extent of soil disturbances. However, the associated soil CO_2-C losses during tillage operations were reduced and similar among different tillage systems. The soil CO_2 flux after rainfall was higher under NT, where it was linearly related to soil temperatures (0.15 × soil temperature–1.06). Soil CO_2 fluxes decreased on the following days as the soil dried. N fertilization affected CO_2 flux in 5 out of 35 observation days, with higher fluxes with N fertilization under conservation tillage systems. Emissions after rainfall events led to large soil CO_2-C losses, and these were of higher magnitude under conservation tillage systems (NT and MT).

1. Introduction

Soil organic carbon (SOC) content determines soil quality and fertility. Moreover SOC is the greatest terrestrial reservoir of carbon. Upon conversion to agriculture, most soils lose one-third to one-half of their SOC content (Lal and Bruce, 1999). Part of this SOC can be restored with adequate crop management practices (i.e. cropping systems, tillage practices and cover crops) and agricultural inputs (fertilizers and irrigation). The use of adequate management practices can help to offset the increase of atmospheric CO_2 concentration while improving soil quality and productivity (Lal, 2004; Johnson et al., 2007). The SOC content is determined by the balance between the rate of C inputs from crop production and the rate of C outputs as CO_2 efflux from decomposition of crop residues and soil organic matter (Paustian et al., 1997). Soil microbial activity transforms plant-assimilated C (input) to SOC or CO_2 that returns to the atmosphere (output). This process leads to a flux of CO_2 from the soil to the atmosphere.

The process of soil CO_2 flux is altered by management practices (e.g. soil tillage operations) and by meteorology (e.g. rainfall events). Additionally, long-term management practices (e.g. tillage systems, N fertilization) will affect soil characteristics and hence soil CO_2 production and flux. Most studies under different environments agree that soil microbial activity is usually limited by C availability and strongly modulated by soil environmental conditions.

Tillage operations lead to different responses that may be related to the cultivation type and history and with the soil type (Calderón et al., 2000), as well as soil conditions when tillage is implemented (Prior et al., 1997; Kessavalou et al., 1998a). Tillage of previously untilled soil under some agroecosystems led to an increase of CO_2 efflux from the soil. This increase starts after tillage operation and it extends for a period of time. This response may be due to aggregate disruption and exposition of protected organic matter to decomposition (La Scala et al., 2008). Tillage systems modify soil environmental conditions and the SOC content and stratification applied after medium- to long-term periods. Soil CO_2 flux may be affected as a response (Franzluebbers et al., 1995; Bono et al., 2008). In cultivated soils, tillage operations lead to a release of gases entrapped in the soil pores (Reicosky et al., 1997): soil CO_2

Abbreviations: TIL, tillage system factor; NIT, Nfertilizer level factor; NT, no-tillage; MT, minimum tillage; CT, conventional tillage; SOC, soil organic carbon; SOM, soil organic matter; SWC, soil water content; ZN, no (zero) N fertilizer application; MN, medium N fertilizer level (60 kg N/ha); HN, high N fertilizer level (120 kg N/ha); Fb, soil CO_2 flux on the day before tillage operations; Fa, soil CO_2 flux immediately after tillage operations; rainfall events: D06, December 2006; S07, September 2007; O07, October 2007; J09, July 2009.

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fluxes occurred as an initial burst of CO_2 emission that is followed by a stabilization of CO_2 flux within hours. The associated CO_2-C loss from the soil during these periods after tillage may be important depending on the characteristics of each system (Alvarez et al., 2001). Rainfall has also great effects on soil CO_2 fluxes that may lead to significant CO_2-C loss (Rochette et al., 1991).

In agroecosystems, soil CO_2 flux follows a seasonal trend in relation to soil environmental conditions and crop phenology. During drought periods, soil CO_2 flux is mainly driven by soil water content (Akinremi et al., 1999). In these ecosystems, precipitation events lead to increased CO_2 emissions from activation of heterotrophic respiration (Inglima et al., 2009), due to a recovery of microbial activity (Borken and Matzner, 2009). Temperature limits the response of soil CO_2 emission to rainfall events (Almagro et al., 2009). However soil tillage operations and precipitations modify the seasonal trends of soil CO_2 emissions (Sanchez et al., 2003). CO_2 fluxes that occur after tillage and precipitation events under these agroecosystems are fairly understood. In Mediterranean agroecosystems, short-term tillage-induced events have been studied in response to different tillage system (Álvaro-Fuentes et al., 2007; López-Garrido et al., 2009).

N management impacts SOC dynamics (Lal, 2009). On the one hand N fertilization has proven to increase the SOC through increasing biomass production and hence C inputs to the soil (Luo et al., 2010). On the other hand, N fertilization affects soil CO_2 flux and hence C outputs from the soil (Sainju et al., 2008; Ding et al., 2007). As a result, N fertilization may affect the SOC content. Khan et al., 2007 and Mulvaney et al., 2009 suggested that the loss of SOC from soils may occur in response to synthetic fertilizers. The interpretations of these studies were rather controversial (Powlson et al., 2010; Reid, 2008). The measurement of in situ soil CO_2 fluxes can also contribute to this discussion of the effects of N fertilization on SOC dynamics. In Mediterranean conditions, to the best of our knowledge, no previous work has explored the effects of N fertilization on soil CO_2 flux.

In this work we studied soil CO_2 fluxes induced by tillage implementation and rainfall events after 10 years of different tillage systems and N fertilization rates. This study is part of a wider study of the long-term effects of N fertilization on SOC dynamics under different tillage systems in a semiarid Mediterranean agroecosystem.

2. Materials and methods

2.1. Site, tillage and N fertilization

A long-term experiment on tillage and N fertilization in winter-barley was initiated in 1996 in Agramunt (41°48′N, 1°07′E; Lleida, Spain) (Cantero-Martínez et al., 2003). Three levels of N fertilization: zero (ZN), medium (MN) –(60 kg N ha^{-1}) and high (HN) –(120 kg N ha^{-1})–, were compared in a factorial design with three tillage systems (no-tillage, NT and minimum tillage, MT(conservation tillage systems); and conventional tillage, (CT-intensive tillage system) in a randomized block design with three repetitions and a plot 50 m × 6 m size.

The soil is Xerofluvent typic (Soil Survey Staff, 1994) with a mean annual precipitation of 430 mm. In 1996 the soil in the Ap horizon (0–28 cm) contained 465 g kg^{-1} of sand, 417 g kg^{-1} of silt and 118 g kg^{-1} of clay, an organic carbon concentration ranging from 6 to 9 g kg^{-1} and pH, from 7.8 to 8.1.

In this long-term experiment, winter-barley was cropped every year under rainfed conditions. By the end of June, after harvest, straw residue was spread over the plot in all the treatments. During the summer–autumn fallow period, the field was mostly free from vegetation for 3–4 months due to dry conditions. In 2008 summer weeds appeared, and a herbicide treatment (glyphosate) was applied at the beginning of September over all the plots to keep the soil free of vegetation. Tillage operations were annually conducted by the end of October or beginning of November. The CT treatment consisted on full inversion tillage operation with moldboard plough to a soil depth of 25–30 cm with almost 100% of the residue incorporated into the soil. The moldboard plow consisted of three bottoms of 0.50 m width.

Intensive tillage operations in 2007 and 2008 were replaced with disk ploughing to a depth of 25–30 cm instead of the one mentioned before. This was due to the soil water conditions at the moment of tillage implementation, too dry in 2007 and too wet in 2008. Disk ploughing consisted of full inversion tillage similar to moldboard ploughing in terms of depth of disturbance, soil loosening and residue incorporation.

The MT treatment consisted of a cultivator pass to a depth of 10–15 cm, with an incorporation of approximately 50% of the crop residue. The plough consisted of 5 rigid shanks spaced 20 cm and a shank width of 5 cm. No soil disturbances were produced in the NT plots. Barley was annually seeded in mid November two–three weeks after the tillage operations. N fertilizer was split into two applications: one-third of the dose previous to tillage as ammonium sulfate (21% N) and two-thirds of the dose at the beginning of tillering as ammonium nitrate (33.5% N).

2.2. Measurements

Soil CO_2 fluxes were measured during autumn tillage operations in four consecutive years (2005–2008 period). An open chamber system (model CFX-1, PPSystems) connected to an infrared gas analyzer (model EGM-4, PPSystems) was used. The chamber has a cylindrical diameter of 21 cm, which covers a soil surface of 346 cm^2. Two regions of 6 m^2 were defined on each plot, and one measurement within each region was taken on each sampling day. The chamber was directly inserted about 1–2 cm deep in the soil. The air flow rate of the chamber was adjusted to 900 mL min^{-1}. Flux readings were taken 3–4 min after the chamber had been inserted into the soil, when readings of CO_2 flux were stable. All measurements were carried out between 09:00 and 13:00 h.

Soil CO_2 fluxes were evaluated by successive measurements over the same regions. For each tillage system, the soil CO_2 flux was measured five times each year; 24 h prior to tillage (−1 day), immediately after tillage implementation (0 h), 2 h after second measurement (2 h), 24 h after tillage (1 day) and 48 h after tillage (2 days). For NT plots, the 2 h sampling was suppressed since the difference in gas fluxes between 0 and 2 h was negligible.

The effects of rainfall events on soil CO_2 flux were evaluated in December 2006, in September and October 2007 and in July 2009. Soil CO_2 flux was measured on the day before and after rainfall events. In September and October 2007, we extended the experimental period after each rainfall event for the observation of the evolution of soil CO_2 flux with subsequent soil drying. CO_2 flux was also affected by 8 mm rainfall during the study of the effects of tillage operations in 2006. We also consider this event on the effects of rainfall on soil CO_2 flux.

Environmental conditions in the soil surface were determined at each sampling point. Soil temperature at 5 cm depth was determined with a had-held probe (TM65, Crison). Gravimetric soil water content (SWC) in the soil surface (0–5 cm depth) was determined by oven drying a soil sample from each sampling point at 105 °C. Daily air temperature and precipitation were recorded at the experimental site in an automated weather station.

The measurements during tillage and during rainfalls were conducted during the fallow periods, when the soil was free from living plants and there was not any live plant root. In December 2006, measurements were conducted at crop emergence, when the con-