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Document downloaded from:

<http://hdl.handle.net/10459.1/58426>

The final publication is available at:

<https://doi.org/10.1016/j.agee.2010.07.015>

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1 **Soil CO₂ fluxes during tillage operations and rainfall events in a Mediterranean**
2 **agroecosystem: effects of tillage systems and nitrogen fertilization**

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1 **ABSTRACT**

2 Management practices can influence soil CO₂ efflux in croplands. Under Mediterranean
3 conditions, soil CO₂ flux responds to tillage and precipitation events with different extent
4 and duration. CO₂ fluxes during these events may constitute a significant part of the annual
5 soil CO₂ emission. Further estimation of these events is required for estimation of the soil C
6 balance and modeling of C dynamics. The long-term effects of tillage practices (NT, no-
7 tillage, MT, minimum tillage and CT, conventional tillage) and N fertilization level (zero,
8 medium, 60 kg N ha⁻¹, and high, 120 kg N ha⁻¹) on soil CO₂ fluxes were measured during
9 tillage operations in four consecutive years (2005-2008 period) and during four rainfall
10 events. In all the four years studied, tillage implementation led to a pulse of soil CO₂ flux.
11 The extent of this response was linearly related with soil CO₂ flux on the day before tillage
12 operations under MT (slope=4.22; R²=0.69; P<0.01) and CT (slope=16.7; R²=0.87;
13 P<0.01) and indicating the extent of soil disturbances. Cumulative soil CO₂ fluxes 48 hours
14 after tillage were similar for different soil tillage and N fertilization treatments.
15 Precipitation events led to sharp increase of soil CO₂ fluxes that decreased as the soil dried.
16 The response of soil CO₂ fluxes to rainfall events was higher in order NT>MT>CT. Under
17 NT, the soil CO₂ flux after rainfall was linearly related to soil temperatures (slope=0.15;
18 R²=0.96, P<0.01). N fertilization affected CO₂ flux occasionally (in 4 out of 35 samplings),
19 with lower fluxes with no N fertilization, and significant interaction with tillage system,
20 where differences among N fertilizer levels were significant under NT and MT, but not
21 under CT.

22 **Abbreviations:** TIL, tillage system factor; NIT, N fertilizer level factor; NT, no tillage;
23 MT, minimum tillage; CT, conventional tillage; SOC, soil organic carbon; SOM, soil
24 organic matter; SWC, soil water content; ZN, no (zero) N fertilizer application; MN,

1 medium N fertilizer level (60 kg N/ha); HN, high N fertilizer level (120 kg N/ha); *Fb*, soil
2 CO₂ flux on the day before tillage operations; *Fa*, soil CO₂ flux immediately after tillage
3 operations; rainfall events: D06, December 2006; S07, September 2007; O07, October
4 2007; J09, July 2009.

5 **Key words:** semiarid, precipitation, tillage, temperature

6 INTRODUCTION

7 Soil organic carbon (SOC) content determines soil quality and fertility. Moreover SOC is
8 the greatest terrestrial reservoir of carbon. Upon conversion to agriculture, most soils lose
9 one-third to one-half of their SOC content (Lal and Bruce, 1999). Part of this SOC can be
10 restored with adequate crop management practices (e.g. cropping systems, tillage practices
11 and cover crops) and agricultural inputs (fertilizers and irrigation). The use of adequate
12 management practices can help to offset the increase of atmospheric CO₂ concentration
13 while improving soil quality and productivity (Lal, 2004; Johnson et al., 2007). The SOC
14 content is determined by the balance between the rate of C inputs from crop production and
15 the rate of C outputs as CO₂ efflux from decomposition of crop residues and soil organic
16 matter (Paustian et al., 1997). Soil microbial activity transforms plant-assimilated C (input)
17 to SOC or CO₂ that returns to the atmosphere (output). This process leads to a flux of CO₂
18 from the soil to the atmosphere.

19 The process of soil CO₂ flux is altered by management practices (e.g. soil tillage
20 operations) and by meteorology (e.g. rainfall events). Additionally, long-term management
21 practices (e.g. tillage systems, N fertilization) will affect soil characteristics and hence soil
22 CO₂ production and flux. It is well sound that soil microbial activity, and hence CO₂
23 production and subsequent soil CO₂ flux, is commonly limited by C availability and
24 strongly modulated by soil environmental conditions.

1 Tillage operations lead to different responses that may be related with the cultivation type
2 and history and with the soil type (Calderón et al., 2000), as well as soil conditions when
3 tillage is implemented (Prior et al., 1997; Kessavalou et al., 1998a). Tillage of previously
4 untilled soil under some agroecosystems led to an increase of CO₂ efflux from the soil that
5 starts with residue incorporation and extends for a period of time due to aggregate
6 disruption and exposition of once protected organic matter to decomposition (La Scala et
7 al., 2008). Tillage systems, applied over the medium- to long-term, modify soil
8 environmental conditions and on SOC content and stratification and consequently soil CO₂
9 flux (Franzluebbers et al., 1995; Bono et al., 2008). In cultivated soils, short-term effects of
10 soil tillage on soil CO₂ fluxes occurred as an initial flush of CO₂ emission followed by a
11 stabilization of CO₂ flux within hours that results from the release of gases entrapped in the
12 soil pores (Reicosky et al., 1997). Thus, tillage implementation produces an associated
13 CO₂-C loss from the soil (Alvarez et al., 2001). Also, rainfall would have a great effect on
14 soil CO₂ flux that may lead abrupt changes (Rochette et al., 1991).

15 In semiarid agroecosystems and during drought periods, soil CO₂ flux is mainly driven by
16 soil water content (Akinremi et al., 1999). In these ecosystems, precipitation events lead to
17 increased CO₂ emissions from activation of heterotrophic respiration (Inglima et al., 2009),
18 due to a recovery of microbial activity (Borken and Matzner, 2009). In Mediterranean
19 agroecosystems, soil CO₂ flux follows a seasonal trend in relation with soil environmental
20 conditions and crop phenology (Álvaro-Fuentes et al., 2008) and temperature limits the
21 response of soil CO₂ emission to rainfall events (Almagro et al., 2009). However soil tillage
22 operations and precipitations modify the seasonal trends of soil CO₂ emissions (Sanchez et
23 al., 2003). CO₂ fluxes that occur after tillage and precipitation events under these
24 agroecosystems are fairly understood. In Mediterranean agroecosystems, previous work on

1 these short-term events has focused on the short-term effects of tillage (Álvaro-Fuentes et
2 al., 2007) as affected by tillage systems.
3 N fertilization affects C inputs to the soil and consequently the CO₂ emission from soil to
4 the atmosphere (Sainju et al., 2008; Ding et al., 2007). In Mediterranean conditions, to our
5 knowledge, no previous work has explored the effects of N fertilization on soil CO₂ flux.
6 As a part of a wider study of the long-term effects of N fertilization on SOC dynamics
7 under different tillage systems in a semiarid Mediterranean agroecosystem, in this work we
8 are presenting and discussing data on soil CO₂ fluxes induced by tillage implementation
9 and rainfall events after 10 years of different treatments of tillage and N fertilization.

10 **MATERIALS AND METHODS**

11 **Site, tillage and N fertilization**

12 A long-term tillage and N fertilization experiment in winter-barley was established in 1996
13 in Agramunt (41° 48'N, 1° 07'E; Lleida, Spain) (Cantero-Martínez et al., 2003). Three
14 levels of N fertilization (zero (ZN), medium (MN) -60 kg N ha⁻¹- and high (HN) -120 kg N
15 ha⁻¹-) were compared in a factorial design with three tillage systems (no-tillage, NT and
16 minimum tillage, MT -conservation tillage systems-; and conventional tillage, CT –
17 intensive tillage system-) in a three repetition randomized block design with a plot size 50
18 m x 6 m.

19 The soil is Xerofluvent typic with a mean annual precipitation of 430 mm. In 1996, before
20 the initiation of the experiment, the soil in the Ap horizon (0-28cm) contained 465 g kg⁻¹
21 sand, 417 g kg⁻¹ silt and 118 g kg⁻¹ clay, an organic carbon concentration ranging from 6 to
22 9 g kg⁻¹ and pH ranging from 7.8 to 8.1.

23 In this long-term experiment, winter-barley was cropped every year under rainfed
24 conditions. By the end of June, after the grain harvest, the straw residue was spread over

1 the plot in all the treatments. Since this moment, the field was kept free from vegetation for
2 three-four months fallow. Tillage operations were annually conducted by the end of
3 October or beginning of November. The CT treatment consisted on an intensive tillage with
4 moldboard ploughing to a depth of 25-30 cm soil surface with almost 100% of the residue
5 incorporated in the soil. The moldboard plow consisted of three bottoms of 0.50 m width.
6 Intensive tillage operations in 2007 and 2008 were replaced with disk ploughing to a depth
7 of 25-30cm instead of moldboard ploughing, due to the soil water conditions at the moment
8 of tillage implementation, too dry in 2007 and too wet in 2008. Disk ploughing consisted in
9 full inversion tillage similar to moldboard ploughing in terms of depth of disturbance, soil
10 loosening and residue incorporation. The MT treatment consisted in a cultivator pass to a
11 depth of 10-15 cm with an incorporation of approximately 50% of the crop residue. The
12 plough consisted of 5 rigid shanks spaced 20 cm apart and with a shank width of 5 cm. No
13 soil disturbances were produced in the NT plots. Barley was annually seeded in mid
14 November two-three weeks after tillage operations. N fertilizer was split in two
15 applications: one-third of the dose previous to tillage as ammonium sulfate (21% N) and
16 two-thirds of the dose at the beginning of tillering as ammonium nitrate (33.5% N).

17 **Measurements**

18 Soil CO₂ fluxes were measured during autumn tillage operations in four consecutive years
19 (2005-2008 period). An open chamber system (model CFX-1, PPSystems) connected to an
20 infrared gas analyzer (model EGM-4, PPSystems) were used. The chamber has a
21 cylindrical diameter of 21 cm, covering a soil surface of 346 cm². Two regions of 6 m²
22 were defined on each plot, and one measurement within each region was taken on each
23 sampling day. The chamber was directly inserted about 1-2 cm deep in the soil. Flow rate
24 of the chamber was adjusted to 900 mL min⁻¹. Flux readings were taken 3 to 4 min after the

1 chamber had been inserted into the soil, when readings of CO₂ flux were stable. All
2 measurements were conducted between 09:00 and 13:00 hours. From other experiments on
3 the area, diurnal variations in summer and autumn have been found to be reduced, and
4 measurements at the given time were assumed to provide estimations of daily soil CO₂
5 emissions for the calculations of cumulated fluxes.

6 The effects of tillage operations on soil CO₂ fluxes were evaluated during tillage operations
7 in four consecutive years (2005-2008). For each tillage system, soil CO₂ flux was measured
8 five times each year (Table 1); 24 hours prior to tillage (-1d), immediately after tillage
9 implementation (0h), two hours after second measurement (2h), 24 hours after tillage (1d)
10 and 48 hours after tillage (2d). For NT plots, the 2h sampling was suppressed since the
11 difference in gas fluxes between 0h and 2h was minimal.

12 The effects of rainfall events on soil CO₂ flux were evaluated in December 2006, in
13 September and October 2007 and in July 2009. Soil CO₂ flux was measured on the day
14 before and after rainfall events. In September and October 2007, we extended the
15 experimental period after each rainfall event for the observation of the evolution of soil
16 CO₂ flux with subsequent soil drying (Table 2). In 2006, when studying the effects of
17 tillage operations, CO₂ flux was also affected by additional 8 mm rainfall, which is
18 considered for discussion on the soil CO₂ fluxes after rainfalls.

19 The measurements during tillage and during rainfalls were conducted during fallow period.
20 During this time, the soil was free from living plants and there was not any live plant root.
21 In December 2006, measurements were conducted at crop emergence, when the
22 contribution of root respiration can be supposed minimal (Rochette et al., 1999a). Emerging
23 green area was cut without altering the soil surface before inserting the soil chamber. For

1 these reasons, the CO₂ efflux during these events can be entirely attributed to microbial
2 respiration and so it can be accounted as net C losses from the soil.

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

8 **Data analysis**

9 Statistical analyses of data were performed with SAS (1990). On each sampling date,
10 analyses of variance (ANOVA) using the general linear model procedure was used was
11 used to detect significance of the main factor effects (Tillage system (TIL) and N fertilizer
12 dose (FNT)) and the interaction factor effect (TILxFNT) on each year). Where effects
13 revealed statistically significant (P<0.05), separation of means was determined by multiple
14 comparisons of least-squares means (P<0.05).

15 Rough estimates of cumulative soil C losses after the rainfall event or tillage were
16 calculated by linearly interpolating CO₂ flux measurements on consecutive days after
17 tillage operations and after rainfall events (trapezoid rule). The accumulated flux of CO₂
18 was divided by the length of the experimental measurement, 2 days for tillage periods, or 1,
19 3 or 6 days for rainfall events, and the soil C loss is reported in kg CO₂-C ha⁻¹d⁻¹ for
20 qualitative comparison among measurements periods.

21

RESULTS

1. Tillage effects on short-term soil CO₂ fluxes

Soil CO₂ flux on the day before tillage operations (-1 in Fig. 1) was significantly affected by the effect of tillage systems (TIL) (Table 3). This response was related to differences in soil environmental conditions (SWC and soil temperature) and organic C availability from changes on SOC concentration and crop residue production.

On day 0, under NT, soil CO₂ flux on day 0 was similar to those on the day before (-1) in three out of the four periods considered indicating steady conditions (Fig 1). Considering the years 2005, 2007 and 2008, soil CO₂ fluxes on these two successive days were similar (slope= 1.03; R²=0.87; P<0.05) (Fig 2), further indicating steady fluxes in that period during these years. However, fluxes in 2006 were not steady due to the effects of a rainfall event and soil drying.

On day 0, under MT and CT, tillage operations induced an immediate burst of CO₂ efflux, ranging from 1 to 8 μmol m⁻² s⁻¹ (Fig. 1), with major differences among years, in agreement the previous studies in the region (Álvaro-Fuentes et al., 2007). Rochette and Angers (1999b) in a prairie under cultivation observed pulses between 7 and 20 μmol m⁻² s⁻¹. Reicosky et al. (1997) observed pulses between 1.6 and 3.2 μmol m⁻² s⁻¹ in a cultivated land. As it has been already described, tillage operations lead to an immediate burst in soil CO₂ emission rate because of an increase on the transport coefficient from soil loosening (Reicosky and Lindstrom, 1993; Reicosky et al., 1997). The CO₂ flux after tillage operations was similar under MT and CT in all years, with no significant differences between these two systems at this moment.

N fertilization led to occasional significant effect on soil CO₂ flux at 2h and 0h observation times respectively in 2006 and 2007 (Table 3). Fluxes under ZN were half those under MN

1 and HN. Interaction between tillage and N fertilizer was significant two days after tillage
2 operations in 2006, with significant effect of N fertilizer level under MT, where soil CO₂
3 fluxes were 0.49, 0.84 and 1.01 $\mu\text{mol m}^{-2} \text{s}^{-1}$ under ZN, MN and HN respectively.

4 The observed burst of CO₂ emission after tillage operation was related to the flux of CO₂ on
5 the previous day. CO₂ flux at this moment is closely related to amount of CO₂ entrapped in
6 the soil atmosphere and that will be released after tillage operations. From this relation
7 between fluxes on the previous day (*F_b*) and fluxes immediately after tillage operations
8 (*F_a*) the slope of the linear adjustment were 4.22 under MT and 16.7 under CT indicating
9 the deeper and consequently higher soil disturbance of this system. Previous work on the
10 region reports an increase immediately after tillage operations from 3 to 15 times greater
11 than the fluxes observed on the day before (Álvaro-Fuentes et al., 2007). In other studies in
12 other agroecosystems, it has been reported an increase of soil CO₂ efflux of 3.8, 6.7, 8.2,
13 and 10.3 times larger than the no-tilled soil for 10, 15, 20 and 25 cm plowing depths
14 (Reicosky and Archer, 2007). Under these conditions we report a similar relation between
15 the CO₂ released immediately after tillage and the CO₂ flux before tillage.

16 In all the years, soil CO₂ fluxes under MT and CT sharply decreased 2 hours after tillage
17 operations in comparison to the flux immediately after tillage operations (Fig. 1). In 2007,
18 under driest conditions (Fig. 3), TIL effect was no longer significant at this moment (Table
19 3). The short-term response will depend on the soil environmental conditions when the soil
20 is tilled (Prior et al., 1997; Kessavalou et al., 1998a) and cultivation history and soil type
21 (Calderón et al., 2000).

22 SWC was higher under NT followed by MT and drier under CT during most samplings
23 (Figs 3). In 2006 and 2007, at 0h and at 2h measurements, SWC significantly also differed
24 among N fertilizer levels. SWC in ZN was on average 0.01-0.02 $\text{g}\cdot\text{g}^{-1}$ ($\text{g H}_2\text{O g}^{-1}$ dry soil)

1 drier than the fertilized treatments (MN and HN). Soil temperatures during the
2 experimental periods ranged between 10 and 20 °C, with similar values under different
3 tillage systems. Average soil temperatures for each sampling are presented in Figure 4.
4 Warmer temperatures were partly responsible for the soil drying, especially in 2006 after an
5 8 mm precipitation event on the day before -1 (Figs. 3 and 4).

6 **2. Rainfall effects on CO₂ fluxes**

7 Soil CO₂ flux on the day before rainfall, was close to 0.5 μmol m⁻² s⁻¹. The CO₂ flux, in
8 μmol m⁻² s⁻¹, after rainfalls were 0.33 after 6 mm in December 2006 (D06), 1.68 after 4
9 mm in September 2007 (S07), 1.42 after 14 mm in October 2007 (O07) and 2.77 after 29
10 mm in July 2009 (J09) (Fig. 5).

11 Soil rewetting led to high increases in soil CO₂ flux in three out of the four periods studied,
12 with significant effect of tillage systems (TIL) (Table 4). Differences among tillage systems
13 were more evident after rainfall events (Fig. 5). In D06, the response depended on the
14 tillage systems and was positive under conservation tillage systems (NT and MT) and
15 negative under CT. In S07 and O07, soil CO₂ flux after rainfall was high and differences
16 among tillage systems were high. Further rewetting in O07 further increased CO₂ flux. In
17 J09, after 23 mm rainfall, soil CO₂ flux increased 8 times those on the day before under
18 conservation tillage systems.

19 In S07 and O07, soil CO₂ fluxes on the following days decreased as the soil dried (Figs. 5
20 and 6). A similar trend was observed under NT after precipitation and the following days
21 concomitant with soil drying (Figs. 1 and 3) that led to 44% decrease between day -1 and
22 day 0 under NT.

23 The response of soil CO₂ to N application (NIT) was occasional, as occurred during tillage
24 operations. In September 3 days after precipitation, and in October on the previous to

1 rainfall event, average flux was $0.55 \mu\text{mol m}^{-2} \text{s}^{-1}$ under ZN and $0.66 \mu\text{mol m}^{-2} \text{s}^{-1}$ on
2 fertilized soil.

3 As found during the tillage implementation periods, the SWC after the rainfall events
4 differed among tillage systems with higher SWC under NT, medium under MT and lowest
5 under CT (Fig. 6). Soil temperature was between 1 and 4 °C higher under CT than under
6 NT, and medium under MT system (Fig 7).

7 Soil CO₂ flux after the observed rainfall events were related to the soil temperatures. Under
8 NT the soil CO₂ flux after the rainfall event showed a significant linear relationship with
9 soil temperatures (slope=0.15, R²=0.96, P<0.01) (Fig. 8), for temperatures between 10.3
10 and 24.2° C. This relationship is similar as that obtained by Rochette et al., 1991 under a
11 maize crop and considering data with volumetric soil water content between 10 and 35 %
12 (R_{soil}= 0.2 T_{soil} -0.74; for T_{soil} between 13 and 33°C). Under MT and under CT there was
13 no clear relation with the soil temperature, indicating that other factors may have been of
14 greater concern during the observed events. Even the increase of soil CO₂ flux after the
15 observed rainfall events has been related with soil temperature under NT, the extent of soil
16 rewetting influences the activation, as observed after additional 11 mm rainfall in October
17 2007, with additional rainfall and rewetting (Fig. 6) and further increase of soil CO₂ flux
18 (Fig. 5).

19 **DISCUSSION**

20 Soil CO₂ flux during the rainfall events as well as on the day before tillage operations were
21 higher under conservation tillage systems (NT and MT) than under CT (Fig. 1 and 5). Soil
22 water status limited soil CO₂ emissions. As observed after rainfall events, once rewetting
23 occurred, temperature determined the extent of the activation of soil CO₂ flux, and soil
24 drying the duration of the activation. Hence during summer and autumn, water limited-

1 seasons in Mediterranean conditions, the effect of rainfalls on soil CO₂ flux is persisting for
2 a period of time depending on the length of time that the soil remains moist (Fierer et al.,
3 2003), and it is not a pulse response, but a period of time during which water-limitation is
4 overcome. Responses of CO₂ fluxes under undisturbed soil in contrast to disturbed soil
5 have been observed in other field experiments with higher response under no-tillage
6 systems or on undisturbed soils in comparison with tilled soils (Kessavalou et al., 1998a;
7 Jackson et al., 2003).

8 The effects of TIL, NIT and the interaction term on soil CO₂ flux (Tables 3 and 4) can be
9 related to differences organic C availability and crop residue production. Annual biomass
10 production differed among tillage systems. Crop residues production was on average 30
11 and 23 % higher under NT and MT than under CT, due to improved water use efficiency
12 under conservation tillage systems in this region (data not shown). Because of tillage
13 operations and residue incorporation in deeper layers, SOC significantly responded to
14 tillage systems and in 2006 the SOC concentration was 12.1, 17.6 and 20.3 g kg⁻¹, in the
15 soil surface (0-5cm soil depth) under CT, MT and NT respectively, but no significant
16 differences at deeper layers, and this pattern on SOC stratification led to a similar pattern
17 on soluble carbon availability, microbial biomass and biochemical activity (Madejón et al.,
18 2009). SOC accumulation and crop residue production enhanced substrate availability.
19 Substrate availability is one major control of the response of soil CO₂ flux to rainfall events
20 (Casals et al., 2009) from the effects on the soil microbial activity. Hence under semiarid
21 Mediterranean conditions, soil CO₂ fluxes after rainfall were more responsive to
22 precipitation events under NT and MT than under CT. Moreover, the increases in SOC
23 concentration is leading to an increase of the capacity of the soil to retain water, as
24 observed on the SWC after rainfall events (Fig. 6).

1 From all the observations in this work, N fertilization effect was only significant in two
2 samplings during tillage operations and two samplings during rainfall events (Table 3 and
3 4). In these two samplings during rainfall the interaction term was also significant (Table
4 4), besides of another sampling during tillage operations in 2006 (Table 3). The interaction
5 indicated N fertilizer application occasionally increased soil CO₂ flux under conservation
6 tillage systems (NT and MT), but were not significant under CT.

7 In a field experiment in Montana, N fertilization increased soil CO₂ emissions by 14% in an
8 annual cropping system, though this effect could be attributed to differences on either root
9 respiration or microbial respiration (Sainju et al., 2008). However during the experimental
10 periods considered in this paper, carried out during fallow periods, there was not any
11 contribution of root respiration to soil CO₂ flux and differences among treatments were
12 ascribed to differences on microbial respiration. The occasional response of soil CO₂ flux to
13 N application in our experiment, and the interaction with tillage systems (Tables 3 and 4)
14 can be related with similar responses on residue production (data not shown). N fertilization
15 led to 10 to 20% increase that led to higher soil cover and slightly wetter conditions and
16 may eventually lead to increased substrate availability and increased soil microbial activity
17 that would hence increase soil CO₂ flux. This may have affected microbial activity and soil
18 CO₂ flux during these moments. In a subhumid environment, N fertilizer applications
19 reduced soil CO₂ flux (Brye, 2006), however the N fertilizer regimes had failed to increase
20 wheat residues levels and other factors may have been involved in this response.

21 The implication of short-term emissions of CO₂ on soil C dynamics was considered in the
22 seven measurement periods studied. Rough estimates of the CO₂-C emissions were
23 calculated for the three rainfall events and four autumn tillage events. CO₂-C emission, on
24 a per day basis, is calculated for different tillage systems and N fertilizer levels (Table 5).

1 The daily CO₂ -C loss after tillage is within the range of values obtained by Ellert and
2 Janzen, 1999, that reported 2.7 kg C ha⁻¹ d⁻¹, during two days, Prior, 1997, that reported 5.0
3 kg C ha⁻¹ d⁻¹, during 8 days after tillage implementation and McGinn et al., 1998, that
4 reported 8.4 kg C ha⁻¹ d⁻¹ during 11 days after tillage. Short-term losses of CO₂-C after
5 tillage are small in terms of C balance (Roberts and Chan, 1990; Álvaro-Fuentes et al.,
6 2008) even after initial cultivation of no-tilled soil (Quincke et al., 2007). Despite the initial
7 flush, tillage operations produced a pulse of CO₂ emission of short duration that leads to
8 little effect on cumulative CO₂-C losses (Table 5).

9 From long-term observations (unpublished data), mean annual soil CO₂ flux rates in this
10 experimental area are around 10 kg CO₂-C ha⁻¹ d⁻¹, and those during summer and autumn
11 are 4 and 7 kg CO₂-C ha⁻¹ d⁻¹, in agreement with similar agroecosystems in semiarid Spain
12 (Sanchez et al., 2003). The calculated rates after rainfall were up to 6 times those mean
13 rates (Table 5). The accumulated CO₂-C losses after rainfalls during fallow period appeared
14 to be of greater importance than those after tillage operations, due to a more persisting
15 effect (Kessavalou et al., 1998b; Ball et al., 1999). Tillage system had substantial effects on
16 CO₂ emissions after rainfalls (Table 5) that must be taken into account when comparing
17 emissions under different tillage systems. Effects of N fertilization on the cumulative fluxes
18 were slight, in accordance with the lack of changes on the SOC content due to long-term N
19 fertilization. Hence, CO₂ emission after rainfalls during the fallow period, especially under
20 semiarid conditions, must be taken into account to accurately estimate annual soil CO₂
21 emissions and for the evaluation of management practices.

22 CONCLUSIONS

23 This experiment highlights the extent of changes on the dynamics of soil CO₂ emission
24 with conservation tillage systems and the contributions of tillage operations and

1 precipitation events on the soil CO₂ emissions in semiarid Mediterranean conditions.
2 Tillage operations led to pulse emissions that were occasionally affected by N fertilization,
3 however these pulse had little effect, and cumulated CO₂ emissions after two days were
4 similar. Increases and decreases of soil CO₂ flux occurred with soil rewetting and soil
5 drying. Under NT, soil CO₂ flux after rainfalls could be related with soil temperature.
6 Emissions after rainfall events are high and must be taken into account when estimating the
7 soil CO₂-C loss in semiarid Mediterranean agroecosystems. During these events,
8 conservation tillage systems (NT and MT) increased the soil CO₂ emission.

9 **ACKNOWLEDGMENTS**

10 This work was supported with by the Comision Interministerial de Ciencia y Tecnologia of
11 Spain (Grants AGL 2004-07763-C02-02 and AGL2007-66320-CO2-02/AGR). Thanks to
12 Carlos Cortés and Silvia Martí for technical assistance and to Jaume Prenafeta for his help
13 after precipitation events. We also acknowledge the Ministry of Science and Innovation for
14 funding the doctorate studies of F.J. Morell.

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15

1 **TABLES**

2 **Table 1.** Calendar of soil CO₂ measurements during tillage operations for each experimental
 3 period.

Year	Tillage date	Time since tillage implementation in hours
2005	3 rd November	-24, 0, 2, 24, 48
2006	25 th October	-24, 0, 2, 24, 48
2007	6 th November	-24, 0, 2, 24, 48
2008	6 th November	-24, 0, 2, 24, 48

4

5 **Table 2.** Calendar of soil CO₂ measurements during rainfall events for each experimental period. -
 6 1, previous day to precipitation event.

Precipitation event (Rainfall)	Precipitation date	Time since precipitation (days)
December 2006 (6mm)	5 th December 06	-1, 1
September 2007 (4mm)	22 nd September 07	-1, 1, 2, 3
October 2007 (14+10mm)	3 rd October 07	-1, 1, 2, 3, 4, 5, 6
July 2009 (29mm)	6 th July 09	-1, 1

7

8

9

1 **Table 3.** Significance of main factors (TIL, tillage system, and NIT, N fertilizer levels) and
 2 the interaction factor (TIL*NIT) on the analysis of variance for each sampling and year before (-
 3 1 day), and after tillage operations (After, 2 hours, 1 day and 2 days), (C.V., coefficient of variation;
 4 NS, non-significant at 0.05 probability level). The number of samples on each sampling was 54
 5 (two samples per plot) but on the 0 hour sampling when only 27 samples were taken (one per plot).

S	Event	C.v.	TIL	NIT	TIL*NIT
Day	2005	31.7	0.0144	NS	NS
	2006	30.6	<.0001	NS	NS
	2007	27.4	0.0005	NS	NS
	2008	47.2	<.0001	NS	NS
0 hour	2005	63.4	0.0005	NS	NS
	2006	55.4	0.0014	NS	NS
	2007	64.6	0.0153	0.32	NS
	2008	56.5	0.0006	NS	NS
2 hours	2005	51.1	0.0107	NS	NS
	2006	25.5	0.0022	0.00	NS
	2007	34.6	NS	NS	NS
	2008	14.7	0.001	NS	NS
1 day after	2005	46.4	0.0123	NS	NS
	2006	35.7	NS	NS	NS
	2007	29.1	<.001	NS	NS
	2008	39.7	0.0063	NS	NS
2 days	2005	45.2	NS	NS	NS
	2006	34.4	0.0060	NS	0.0057
	2007	33.5	0.0402	NS	NS
	2008	32.5	<.0001	NS	NS

6

7

1 **Table 4.** Significance of main factors (TIL, tillage system, and NIT, N fertilizer levels) and
 2 the interaction factor (TIL*NIT) on the analysis of variance for each sampling and year before (-
 3 1 day), and after rainfall events (After, 2 hours, 1 day and 2 days), (C.V., coefficient of variation;
 4 NS, non-significant at 0.05 probability level). S. Sampling; d, days. The number of samples on each
 5 sampling was 54 (two samples per plot).

S	Event	C.V.	TIL	NIT	TIL*NIT
Day before	D06	29.5	0.008	NS	NS
	S07	45.4	<.0001	NS	NS
	O07	33.3	0.02	0.02	0.04
	J09	25.7	NS	NS	NS
Day after	D06	29.5	<.0001	NS	NS
	S07	34.7	<.0001	NS	NS
	O07	39.6	<.0001	NS	NS
	J09	19.7	0.02	NS	NS
2 d after	S07	39.9	<.0001	NS	NS
	O07	38.8	<.0001	NS	NS
3 d	S07	41.6	<.0001	0.05	0.02
	O07	35.4	<.0001	NS	NS
4 d	O07	34.6	<.0001	NS	NS
5 d	O07	37.9	<.0001	NS	NS
6 d	O07	43.9	<.0001	NS	NS

6

7

1 **Table 5.** Estimations of daily soil CO₂-C loss from tillage-implementation periods (Tillage) and
 2 rainfall events (Rainfall), in kg of C per hectare and per day. The number in brackets on the Period
 3 column indicates the number of observation days after tillage or rainfall events.

	Period	Cumulative CO ₂			Cumulative CO ₂		
		NT	MT	CT	ZN	MN	HN
Tillage	2005 (2)	4.7	8.8	6.6	6.7	7.6	7.1
	2006 (2)	6.4	9.3	7.2	6.2	8.2	9.2
	2007 (2)	3.3	5.3	4.1	4.2	4.5	4.3
	2008 (2)	10.7	14.4	10.0	12.6	13.0	11.0
Rainfall	Dec 06 (1)	5.5	4.2	0.7	3.6	3.5	3.3
	Sep 07 (3)	14.7	12.4	6.6	10.0	12.9	10.9
	Oct 07 (6)	19.3	17.0	6.3	14.4	14.9	13.7
	Jul 09 (1)	28.1	33.4	21.8	25.9	27.0	30.7

4

5

1 **FIGURE CAPTIONS**

2 **Fig 1.** Soil CO₂ fluxes during tillage operations (CT, conventional tillage; MT, minimum tillage;
3 NT, no-tillage) in four consecutive years. Vertical bars indicate standard deviations of the means for
4 each tillage system.

5

6 **Fig 2.** Relation of soil CO₂ efflux the day before tillage (-24h) and immediately after tillage
7 implementation (0h), for each tillage system (CT, conventional tillage; MT, minimum tillage; NT,
8 no-tillage). Nine points per treatment corresponding to observations in three years (2005, 2007 and
9 2008) and three N fertilization levels for each year and tillage system. Lines were obtained from
10 linear adjustments for each tillage system. *Fb* and *Fa* are fluxes before and after tillage operations.

11

12 **Fig 3.** Gravimetric soil water content (SWC) in the top 5 cm during the tillage periods studied
13 under different tillage treatments (CT, conventional tillage; MT, minimum tillage; NT, no-tillage),
14 line plot. Different letters indicate mean separation among tillage systems (P<0.05). Mean
15 separation on the following days was the same as indicated for day 1.

16

17 **Fig 4.** Mean Trends of soil temperatures at 5 cm soil depth on each experimental period in different
18 years, 2005-2008, for the different tillage systems: CT, conventional tillage; MT, minimum tillage;
19 and NT, no-tillage.

20

21 **Fig 5.** Soil CO₂ fluxes before and after rainfall events (D06, December 2006; S07, September
22 2007; O08, October 2007; 09, July 2009) under different tillage systems (CT, conventional tillage;
23 MT, minimum tillage; NT, no-tillage). Vertical bars indicate standard deviations of the means for
24 each tillage system.

25

1 **Fig 6.** Gravimetric soil water content (SWC) in the top 5 cm previous and after rainfall events
2 under CT, conventional tillage; MT, minimum tillage; and NT, no-tillage. In -1, values on the
3 previous day are indicated. The periods are D06, December 2006; S07, September 2007; O08,
4 October 2007; 09, July 2009. Different letters indicate mean separation among tillage systems
5 ($P < 0.05$). In S07 and O07 mean separation on the following days was the same as indicated for day
6 1.

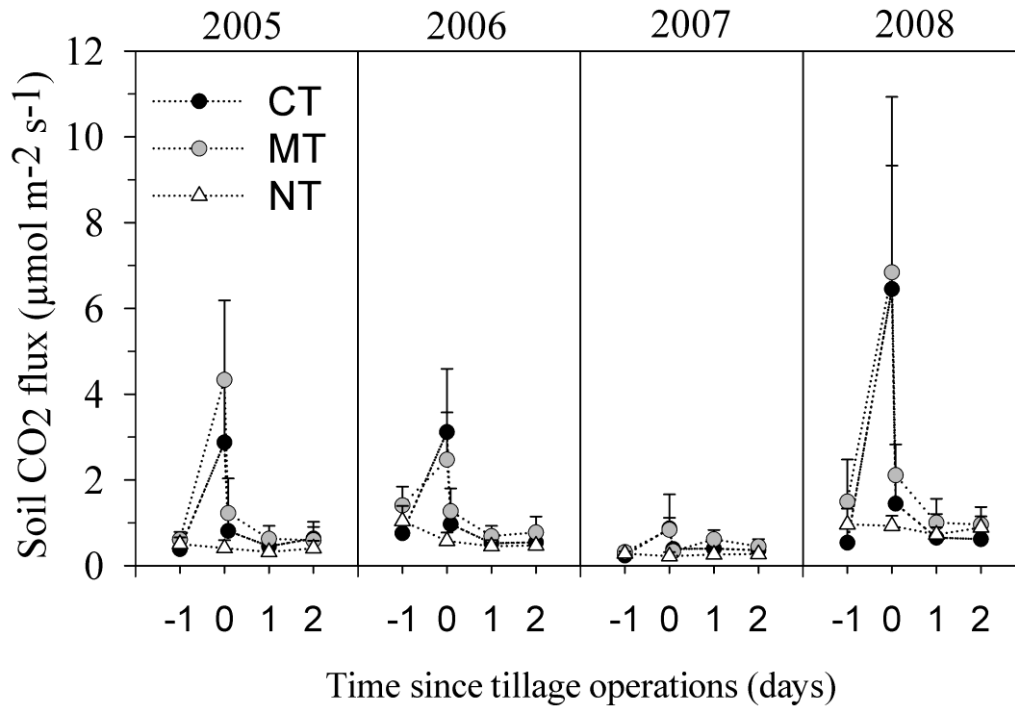
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8 **Fig 7.** Trends of soil temperatures at 5 cm soil depth on each experimental period: D06, December
9 2006; S07, September 2007; O08, October 2007; for the different tillage systems: CT, conventional
10 tillage; MT, minimum tillage; and NT, no-tillage.

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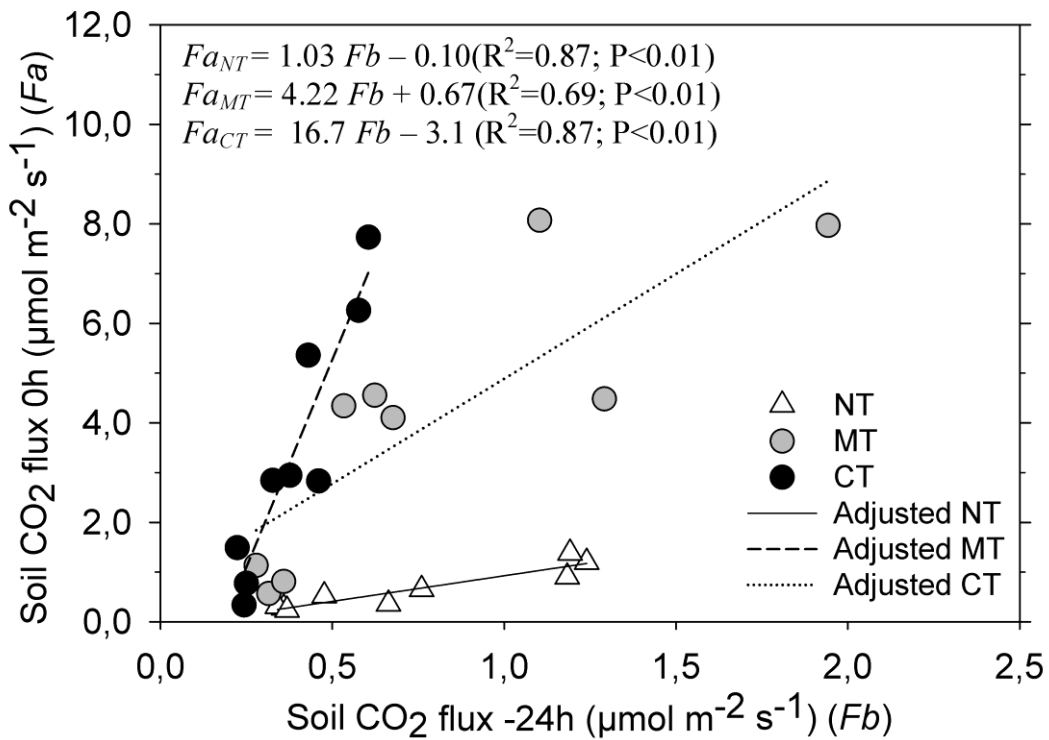
12 **Fig 8.** Relation of soil CO₂ flux after rainfall (1) and temperature, for each tillage system (CT,
13 conventional tillage; MT, minimum tillage; NT, no-tillage) on the day after rainfall events. Ellipses
14 indicate the rainfall events considered: O06, October 2006; D06, December 2006; S07, September
15 2007; O07, October 2007; J09, July 2009. The amount precipitated (in mm) is also indicated for
16 each event. The adjusted line is drawn for NT system. The adjustments were not significant under
17 MT and CT ($P < 0.05$).

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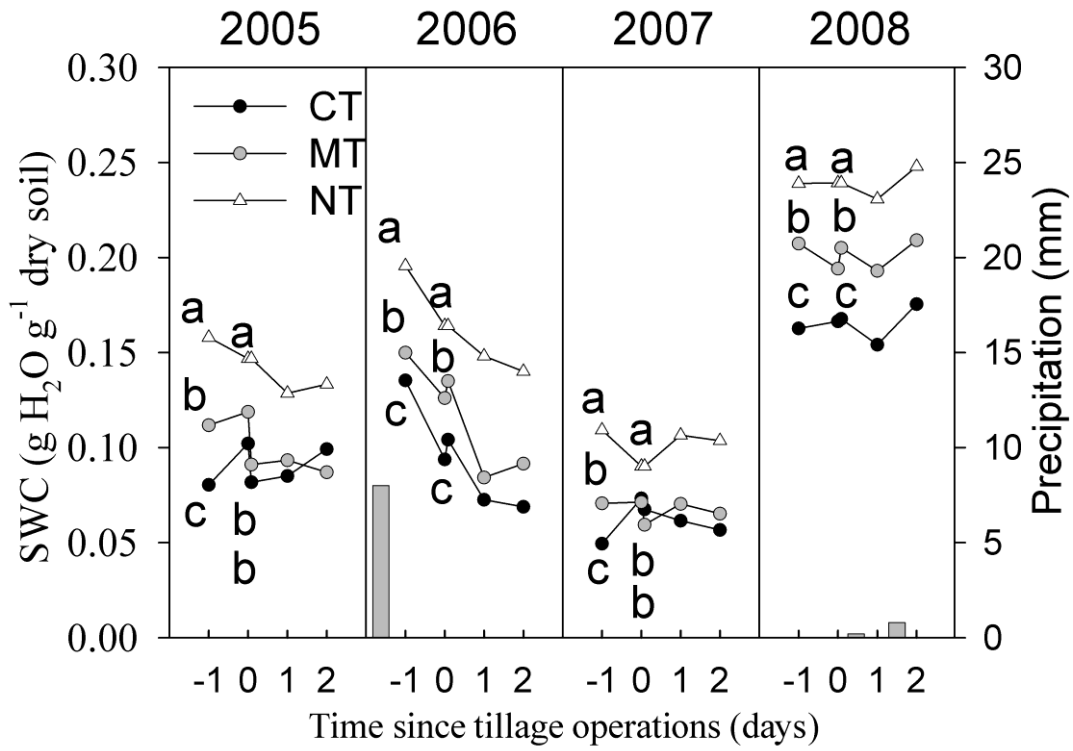
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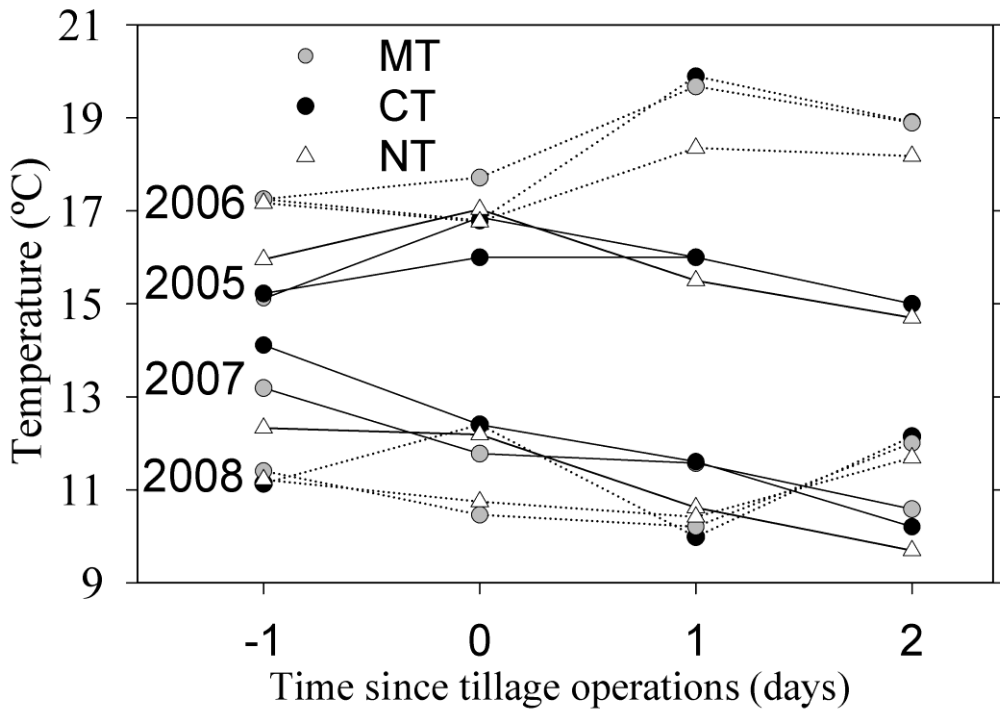


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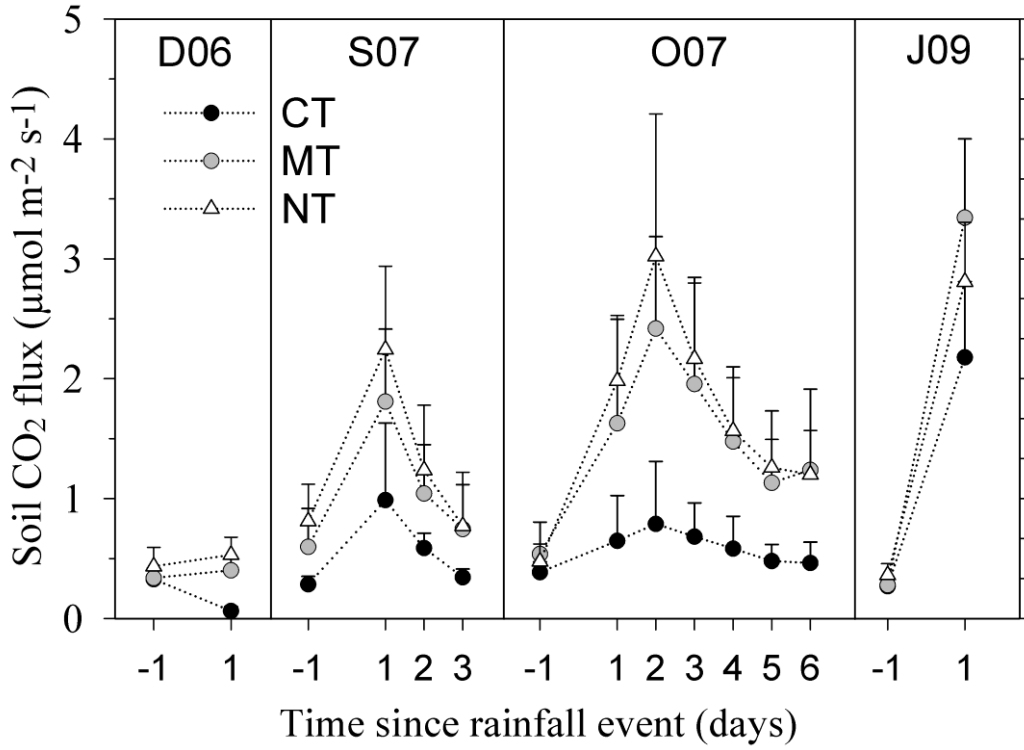
4 Figure 2



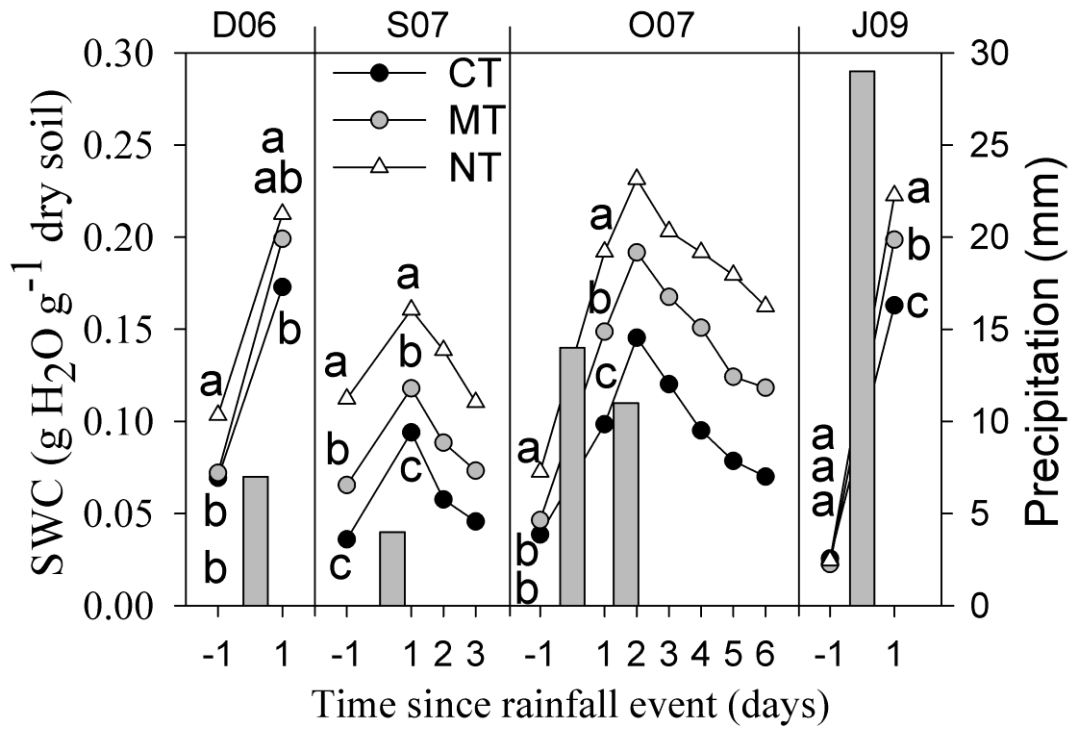
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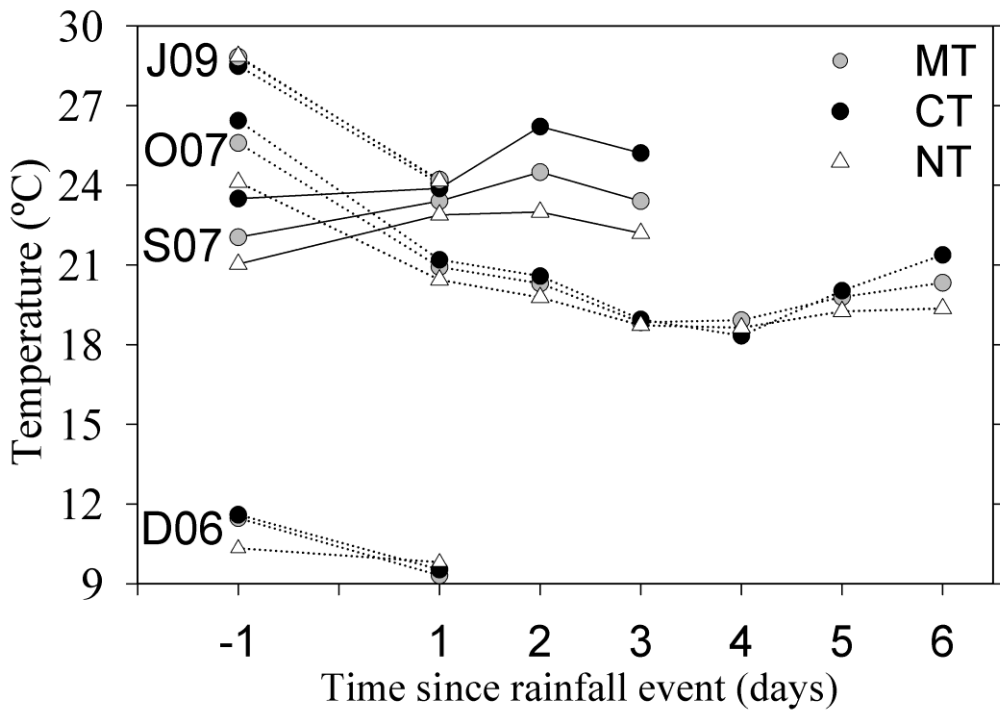
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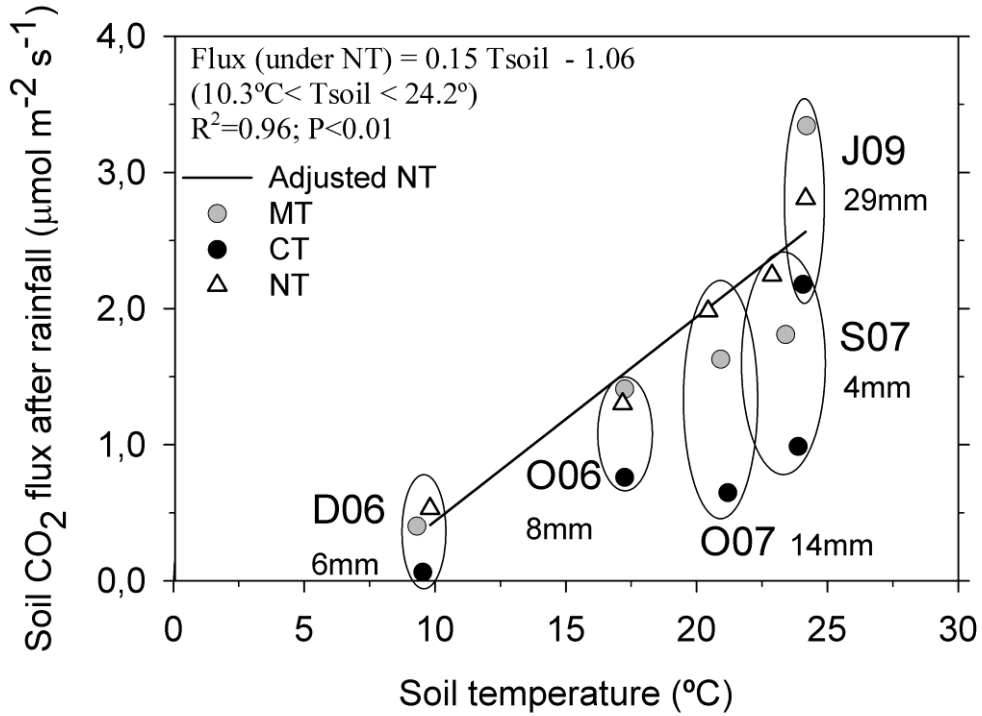
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