

Full Length Research Paper

Effect of tillage practices on the soil carbon dioxide flux during fall and spring seasons in a Mediterranean Vertisol

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In this study, we assessed the effect of conventional tillage (CT), reduced (RT) and no tillage (NT) practices on the soil CO₂ flux of a Mediterranean Vertisol in semi-arid Morocco. The measurements focused on the short term (0 to 96 h) soil CO₂ fluxes measured directly after tillage during the fall and spring period. Soil temperature, moisture and soil strength were measured congruently to study their effect on the soil CO₂ flux magnitude. Immediately after fall tillage, the CT showed the highest CO₂ flux (4.9 g m⁻² h⁻¹); RT exhibited an intermediate value (2.1 g m⁻² h⁻¹) whereas the lowest flux (0.7 g m⁻² h⁻¹) was reported under NT. After spring tillage, similar but smaller impacts of the tillage practices on soil CO₂ flux were reported with fluxes ranging from 1.8 g CO₂ m⁻² h⁻¹ (CT) to less than 0.1 g CO₂ m⁻² h⁻¹ (NT). Soil strength was significantly correlated with soil CO₂ emission; whereas surface soil temperature and moisture were low correlated to the soil CO₂ flux. The intensity of rainfall events before fall and spring tillage practices could explain the seasonal CO₂ flux trends. The findings promote conservation tillage and more specifically no tillage practices to reduce CO₂ losses within these Mediterranean agroecosystems.

Key words: Tillage, CO₂ flux, seasonal variability, Vertisol, semi-arid Morocco.

INTRODUCTION

The important role of CO₂ emissions from soils in the carbon cycle has (only) been clearly recognized for nearly a decade (Schlesinger and Andrews, 2000). Due to the large order of magnitude, small changes in soil CO₂ flux across large areas can produce a great effect on CO₂ atmospheric concentrations (Lal, 2004).

Soil plowing is a principal cause of CO₂ emission from croplands leading to a depletion of soil organic matter

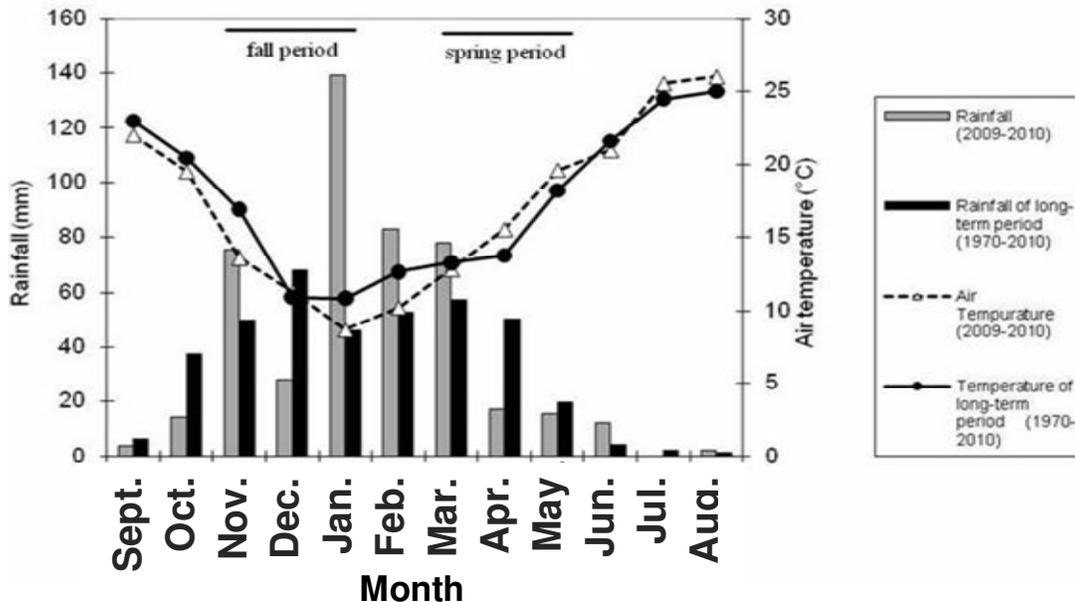
content (Paustian et al., 1997; Six et al., 2002; Lal, 2004). Increase of soil CO₂ emission after tillage was reported by several authors from North America and Europe (Reicosky and Lindstrom, 1993; Ellert and Janzen, 1999). Additionally, Reicosky et al. (1997) explained the increase in CO₂ flux immediately after tillage by a physical release of CO₂ entrapped in soil pores from previous microbial activity rather than the changes in microbial activity at the time of tillage. The magnitude of soil CO₂ flux, at tillage period, depends on the degree and time of soil disturbance as well as on the soil conditions, basically soil moisture and temperature, (Prior et al., 2004; Alvaro-Fuentes et al., 2007). Several studies have observed seasonal CO₂ flux patterns associated with fall or spring tillage and some authors have reported

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Abbreviations: CO₂, Carbon dioxide; NT, no tillage; CT, conventional tillage; RD, reduced tillage.

Table 1. Selected soil properties at the start of the experiment.

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	pH (1:1 H ₂ O)	P ₂ O ₅ (mg/kg)	K ₂ O (mg/kg)
0-20	50.0	37.3	12.7	7.83	19.61	323
20-40	51.3	38.2	10.5	8.26	4.24	184
40-90	52.5	35.1	12.4	8.60	0.53	145

**Figure 1.** Long-term average and 2009 to 2010 cropping season values of rainfall and temperature at the Merchouch research station.

that soil microclimate conditions during tillage events played an important role in CO₂ emission. Reicosky and Lindstrom (1993) and La Scala et al. (2001) reported that the increased CO₂ losses during fall tillage were due to a higher degree of soil disturbance and residue incorporation in soil. Similar findings have been reported during spring tillage practices (Reicosky et al., 1997; Ellert and Janson, 1999; Prior et al., 2004). Other authors did not detect an immediate sharp increase of soil CO₂ following spring tillage and explained this by the impact of soil climate parameters (soil moisture and temperature) on soil respiration during tillage (Hendrix et al., 1988).

In the Mediterranean region, the tilled soils are generally characterized by relatively low soil moisture contents and high temperatures. This research aimed to assess the soil carbon flux under these climatic conditions of fall and spring tillage. Hence, the specific objectives of this study were (1) to quantify the seasonal, short (0 to 24 h) and midterm (24 to 96 h) CO₂ flux after fall and spring tillage in response to contrasting tillage systems and (2) to identify the soil properties that may explain variations in the soil respiration. The obtained results contribute to a better understanding of seasonal CO₂ fluxes in general and to define the optimum tillage operations that can

decrease soil CO₂ emission of Vertisols in the semi-arid Mediterranean region.

MATERIALS AND METHODS

Location, climate and soil

The experiment was conducted at the Merchouch research station of the National Institute of Agricultural Research (INRA), located 60 km south of Rabat (Latitude 33°37' N and Longitude 6°43' W). The site is characterised by a flat topography and is dominated by poorly drained Vertisols (Chromic Calcixererts) that are slightly alkaline and have low organic matter contents but adequate phosphorus (P) and potassium (K) levels in the surface horizons (Table 1).

The mean long-term annual precipitation and temperature are 410 mm and 23°C, respectively. Monthly average precipitation and temperature during the 2009 to 2010 cropping season as well as the long term (40-year) average values are shown in Figure 1. Daily temperature and precipitation were measured using automated weather stations nearby the experiment.

Experiment layout and treatments

The study was conducted on a 1.5 ha plot that has been under fallow and disked in spring for weed control during 2 years before

starting the experimentation in 2009. The land was subdivided into 2 equal subplots of 0.75 ha. The first subplot was used for fall tillage practices and the second for spring tillage operations. On 14 November 2009, the first subplot was divided into 12 small plots (50 × 10 m) arranged in a randomized complete block design with 4 treatments, each replicated 3 times. The treatments were (1) disk plough; and (2) chisel as conventional tillage; (3) tine harrow as reduced tillage and (4) no tillage. In spring (12 April, 2010), the same tillage treatments were applied in the second subplot using the same experimental design.

The disk plough practice consisted of a tandem disk harrow (John Deere type -215) operated at about 25 cm depth and with a width of 4 m. The disk blades were spaced at 22.8 cm and had a radius of 25 cm. The disk angle was adjusted to about 14.5°. The chisel treatment operated at 20 cm and consisted of 11 rigid shanks of 18 cm width and spaced 28 cm apart. The rigid tine harrow consists of four bars. The harrow was tilling at less than 15 cm soil depth with a width of 1.8 m. In the last treatment, the no-tillage plots were left undisturbed. The soil organic carbon and the amount of residues were the same for the different tillage treatments.

Soil CO₂ measurement

Soil CO₂ emission was measured using a chamber system (ACE-Automated Soil CO₂ Exchange System). Measurements are typically made by measuring the rise in CO₂ concentrations inside the chamber. The chamber automatically opens between analysis cycles allowing ambient conditions to reach the soil. Soil CO₂ flux was calculated from the difference in CO₂ concentrations between air entering and leaving the chamber. The chamber had a cylindrical diameter of 23 cm, covering a soil surface of 415 cm². To prevent CO₂ leakage to atmosphere, the chamber was inserted 5 cm into the soil. The first flux reading was taken 3 min after the chamber was installed in order to avoid possible unrealistic values caused by the disturbance produced after placing the chamber into the soil (Pumpanen et al., 2004).

In each of the 12 small plots, soil CO₂ flux was measured randomly at 24 h before and immediately after tillage operations with 24 h interval (0, 24, 48 and 96 h) in fall and spring. To determine the cumulative CO₂ flux, a trapezoidal function was used (Alvaro-Fuentes et al., 2007).

Soil water content and soil temperature

Soil temperature and water content were measured at the same times and locations when CO₂ emission was measured. A soil sample was collected at the surface horizon (0 to 5 cm) to determine the gravimetric soil water content by oven drying at 105°C. Soil temperature was measured with a hand-held probe (ECT, decagon model) which was inserted 5 cm into the soil near the CO₂ chamber.

Soil strength

Immediately after tillage operations, soil strength was measured throughout the topsoil 50 cm soil depth at 10 randomly located points in each of the treatments. Measurements were done using a Rimik CP- 20 cone penetrometer (base area 2 cm², angle 60°). The initial soil water content was determined by the gravimetric method in order to take into account the effect of soil moisture on soil strength.

Statistical analysis

The collected data were subjected to a statistical analysis using

SPSS. Since we are interested in comparing the tillage effect on CO₂ flux for each season and each time period, analysis of variance (ANOVA) was used to study the difference between tillage treatments and least significant difference method (LSD) was applied for comparison of treatment means. Correlations between the soil CO₂ flux and soil temperature, soil moisture and soil strength were determined and tested for their significance using the Pearson correlation coefficient.

RESULTS AND DISCUSSION

ANOVA was done, reconsidering all factors (season, time and tillage). The result of this analysis showed that there is a very highly significant difference ($p < 0.001$) between the two seasons (fall, spring). Therefore, the subsequent analysis was done separately for each season.

Soil CO₂ emission in fall tillage

Figure 2 shows that both the conventional (chisel and disk) and reduced (harrow) tillage practices in the fall both caused an immediate sharp increase in soil CO₂ flux within 24 h time. In contrast, the no-tillage practice did not result in a significant change of the soil CO₂ flux.

The chisel tillage showed the highest CO₂ fluxes (4.9 g m⁻² h⁻¹) followed by the disk tillage (3.9 g m⁻² h⁻¹). The reduced tillage (harrow) exhibited intermediate values (2.1 g m⁻² h⁻¹) followed by the no-tillage treatment, which had the lowest CO₂ flux (0.7 g m⁻² h⁻¹). The 4 treatments were highly significantly different from each other ($p < 0.001$).

These findings reflect the degree of soil disturbance that the chisel and disk treatments implemented. In fact, the disk and chisel treatment resulted in a more soil disturbance (Raper, 2002). 24 h after tillage, the CO₂ flux had already decreased to remain more or less constant up to the end of the measurements (Figure 2).

The same trend was reported by Alvaro-Fuentes et al. (2007) under semi-arid conditions in Spain, where the CO₂ flux immediately obtained after fall tillage ranged between 3 to 13 g m⁻² h⁻¹, while the no-tillage treatment had a lower CO₂ value (less than 1 g m⁻² h⁻¹). Similarly, Reicosky et al. (1997) reported that the amount of CO₂ emitted immediately after tillage was proportional to the degree of soil disturbance produced while no-tillage was not inducing any significant CO₂ flux.

Soil CO₂ emission in spring tillage

The soil CO₂ emissions were lower in the spring tillage treatments compared to those observed in the fall tillage operations (Figure 3). CO₂ flux values ranged from 0.8 (harrow) to 1.8 g m⁻² h⁻¹ (disk). The chisel treatment had an intermediate value 1.4 g m⁻² h⁻¹. No significant difference was observed between the disk and chisel treatments, but the reduced tillage and no-tillage

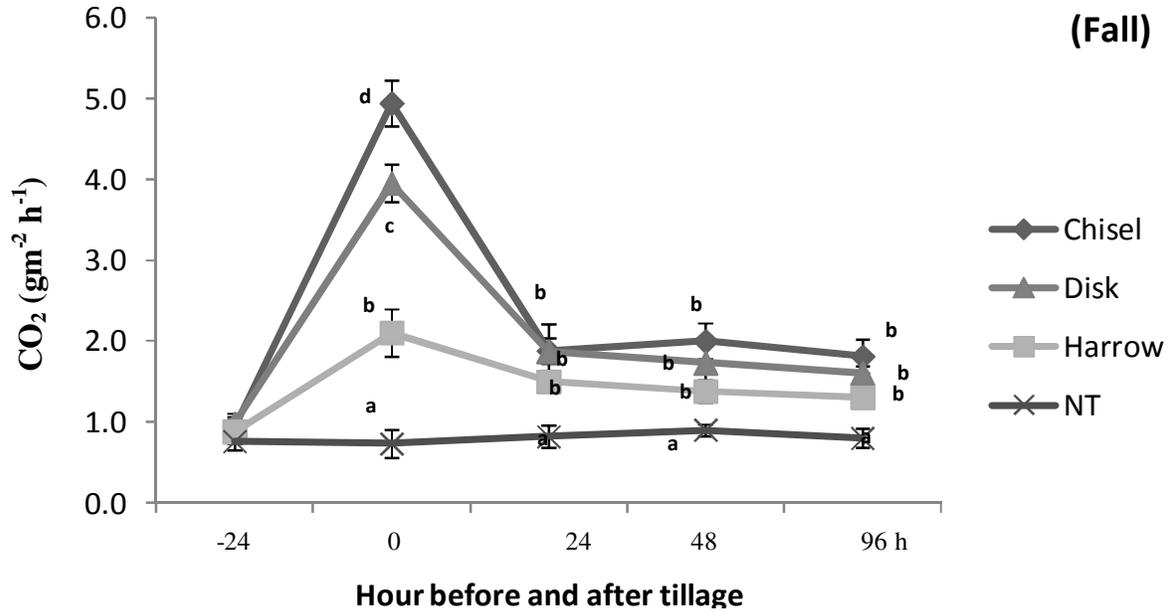


Figure 2. Soil CO₂ flux associated with fall tillage treatments (for the same hour, treatments with the same letter are not significantly different, (LSD test, p<0.05).

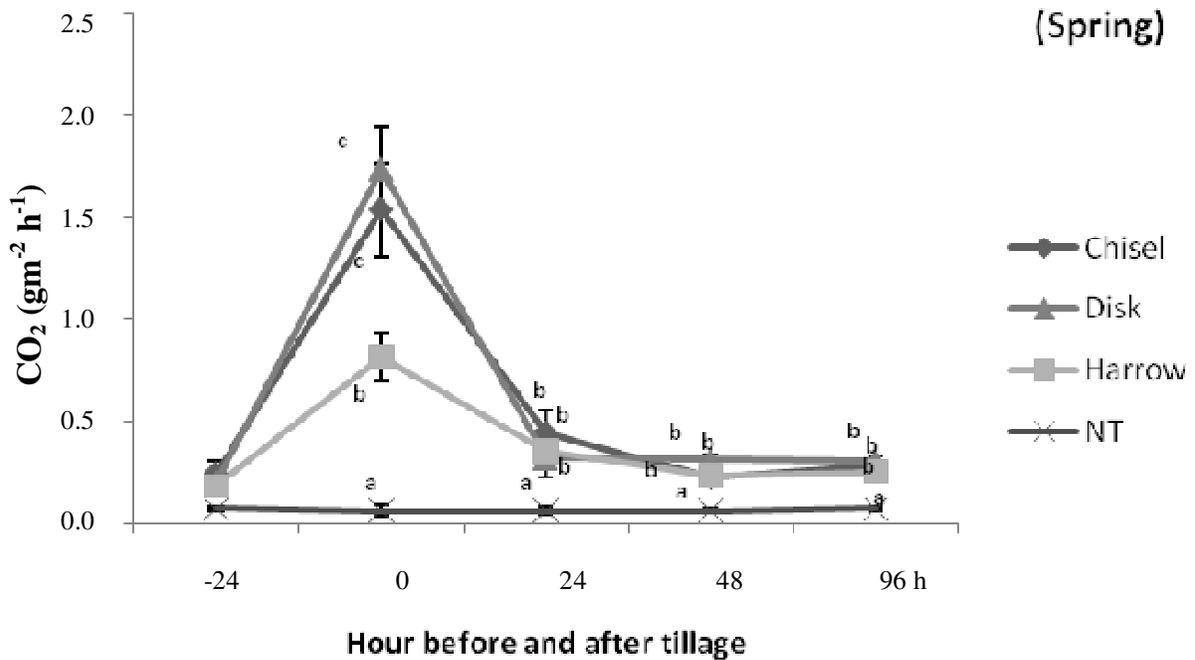


Figure 3. Soil CO₂ flux associated with spring tillage treatments (for the same hour, treatments with the same letter are not significantly different, (LSD test, p<0.05).

treatments exhibited significantly lower CO₂ fluxes. Alvaro-Fuentes et al. (2007) found a similar trend in CO₂ fluxes that ranged between 0.1 and 1.2 g m⁻² h⁻¹ immediately after no tillage and conventional spring tillage, respectively.

Effect of soil temperature and moisture content on the soil CO₂ flux

Figure 4 shows that the soil water content (SWC) and soil temperature (T) measured at 24h time steps before and

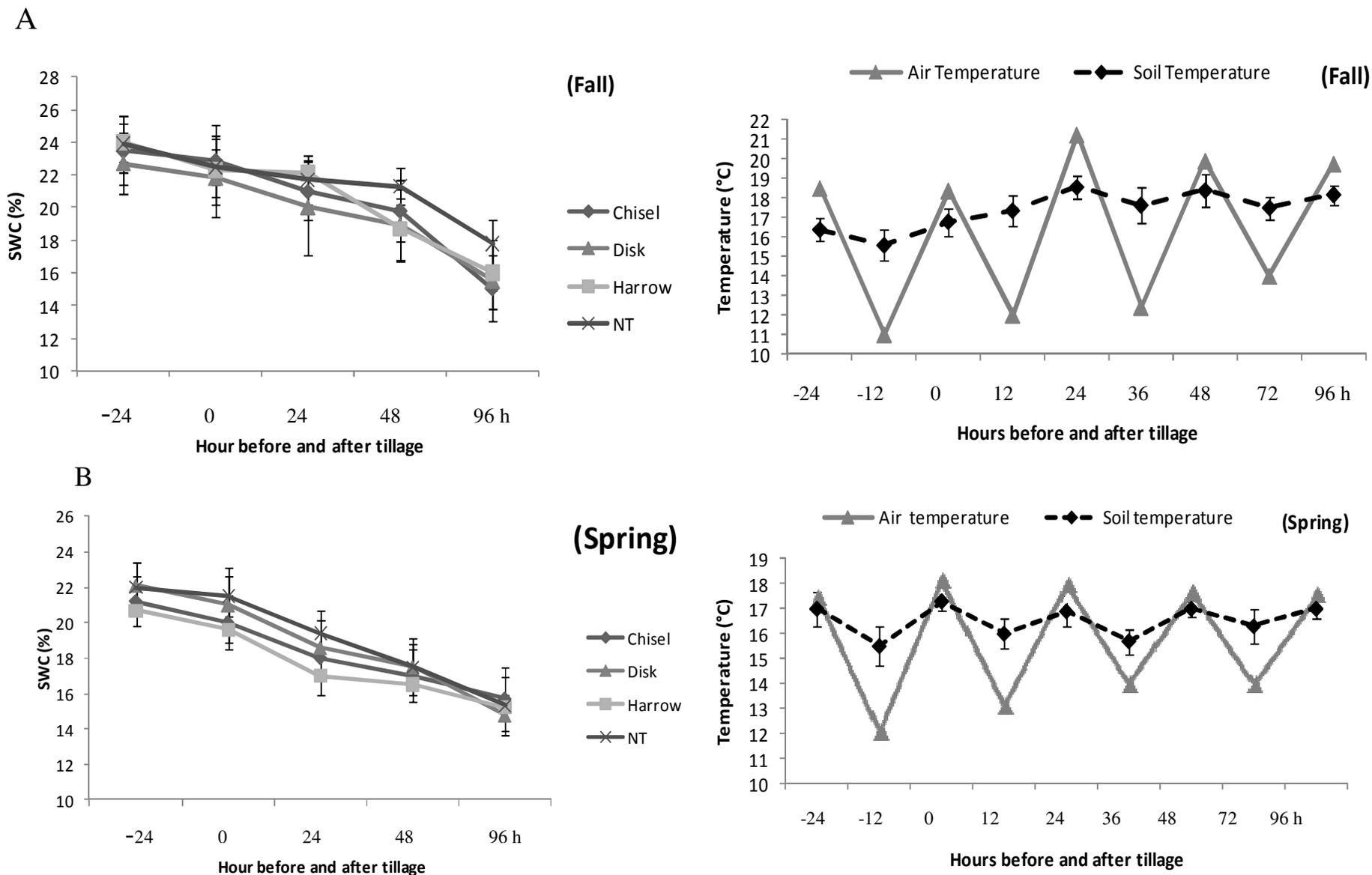


Figure 4. Topsoil (0 to 5 cm) water content (SWC) under different tillage treatments and mean soil (0 to 5 cm) and air temperature before and after tillage during the (a) fall and (b) spring. (*) means the presence of significant differences between treatments.

Table 2. Pearson's correlation coefficients between soil CO₂ flux and soil water content and soil temperature in fall and spring tillage.

Variable	CO ₂ flux (Fall)		CO ₂ flux (Spring)	
	r	p	r	p
SWC	0.22	0.54	0.42	0.51
T	0.05	0.91	0.36	0.19

SWC - soil water content at (0-5 cm); T - soil temperature at (0-5 cm).

after the tillage applied in fall and spring. For all treatments, soil moisture decreased slightly after tillage events in fall and spring but no significant difference was observed between tillage treatments in both seasons. Mrabet (2002) reported that the soil moisture decrease after tillage is due to high soil water evaporation in this semi-arid area.

Also, soil surface (0 to 5 cm) temperature (T) was not significantly affected by tillage practices and no significant differences were observed between treatments at fall and spring. Several authors reported similar insignificant effects of tillage operations on soil temperature and moisture in similar semi-arid conditions (Alvaro-Fuentes et al. 2007).

Soil CO₂ flux observed in fall and spring period were not correlated to soil water content (SWC) nor to temperature (T) measured at 0 to 5 cm topsoil layer (Table 2). The absence of significant correlation between T and SWC and CO₂ flux may be related to the fact that those parameters were assessed at surface horizon (0 to 5 cm) only, whereas soil tillage operations were affecting the deeper soil horizons.

Soil strength

The influence of tillage practices on soil strength measured one hour after tillage is shown in Figure 5. The cone index (C.I.) varied with treatments and depths. The C.I. at 0 to 10 cm depth was significantly higher under no-tillage compared to the other treatments. This is explained by the immediate effect of soil disturbance under those tillage treatments compared to the no till plots. However, at a depth more than 10 cm, no statistically significant differences in C.I. were found between reduced and no tillage. The chisel and disk treatments exhibited the same trends in both fall and spring.

Soil strength of the topsoil (15 cm) was significantly negatively correlated with the soil CO₂ flux during fall and spring periods (Table 3). At 20 to 30 cm depth, the correlation was not statistically significant, but clearly showed a negative trend. As C.I. is used as indicator for soil disturbance (Carter et al., 2007), our results showed that soil CO₂ flux is correlated to the degree of soil disturbance near the soil surface.

Cumulative CO₂ emission during fall and spring tillage

Figure 6 indicates the cumulative soil CO₂ emissions using a simple trapezoidal integration function from 0 to 96 h after tillage in all treatments during the fall and spring periods. In fall period, no significant difference in cumulative CO₂ loss was observed between the chisel and disk tillage (about 155 g m⁻²). The reduced tillage (harrow) exhibited intermediate values (104 g m⁻²) followed by the no-tillage treatment, which had the lowest CO₂ flux (56 g m⁻² h⁻¹). The same trend was observed in spring period. In fact, no significant difference in cumulative CO₂ loss was observed between the chisel and disk tillage (43 g m⁻²). The reduced tillage (harrow) exhibited intermediate values (24 g m⁻²) followed by the no-tillage treatment, which had the lowest CO₂ flux (6 g m⁻² h⁻¹).

From Figure 6, we conclude that the cumulative CO₂ higher during fall period compared to spring period. This difference in seasonal CO₂ fluxes losses during spring and fall can be explained by the greater build-up of CO₂ in the soil at the time of fall tillage due to microbial breakdown of easy decomposable organic substrates (Prior et al., 2004). Also, the soil CO₂ reservoir at the time of spring tillage is expected to be lower due to winter losses attributable to both microbial respiration and physical displacement of soil CO₂ as a result of regular rainfall (Harper et al., 2005).

In fact, in our case study, before fall period (September and October 2009) only 40 mm rainfall occurred in contrast with 300 mm rainfall that occurred before spring period (from January to March 2010) (Figure 1).

Conclusion

This research demonstrates that soil disturbance increases CO₂ flux immediately after tillage of a semi-arid Vertisol. Yet, the magnitude of the CO₂ flux changes through the year, with fall tillage exhibiting much higher CO₂ emissions than spring tillage. The soil CO₂ flux under no tillage was lower than other treatments during fall and spring periods. The tillage-induced flush CO₂ was attributed most probably to the soil disturbance, thereby reducing soil strength and promoting CO₂ diffusion. These findings promote the use of no tillage practices to

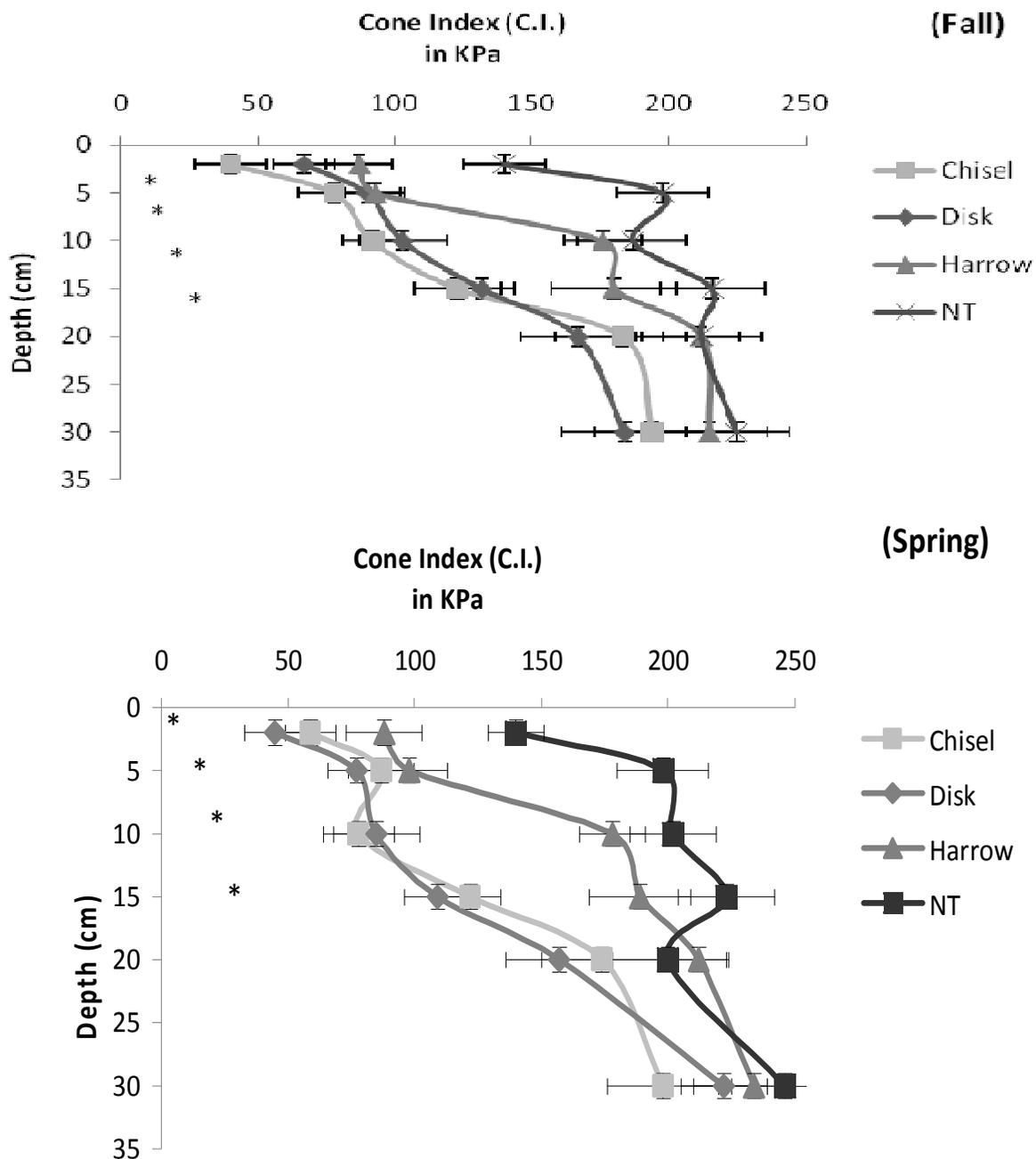


Figure 5. Soil strength (C.I.) measured 1 h after tillage under different treatments, during fall and spring period. At each depth, (*) means the presence of significant differences between treatments.

Table 3. Pearson's correlation coefficients between soil CO₂ flux and soil cone index per depth in fall and spring tillage.

Variable	CO ₂ flux (Fall)		CO ₂ flux (Spring)	
	r	p	r	p
C.I. (0-10 cm)	-0.64	0.032	-0.56	0.045
C.I. (10-20 cm)	-0.45	0.054	-0.38	0.063
C.I. (20-30 cm)	-0.23	0.141	-0.31	0.119

C.I. – soil cone index.

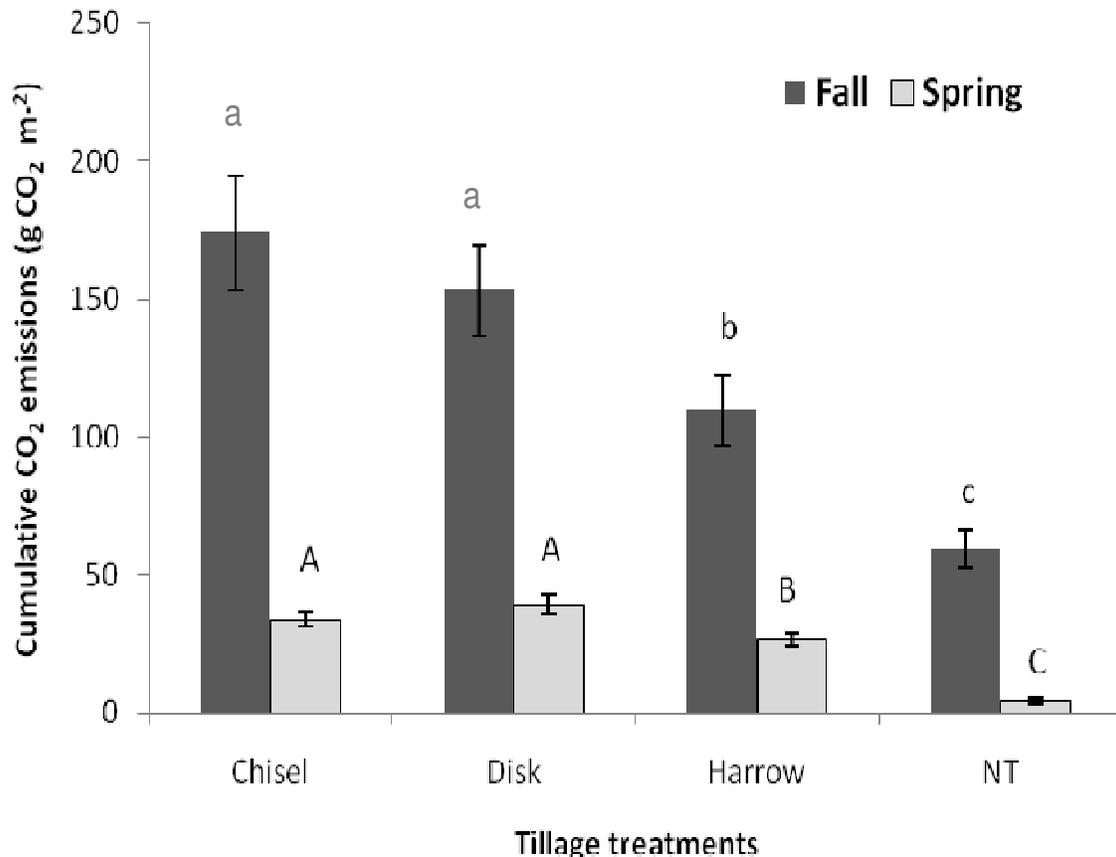


Figure 6. Cumulative CO₂ flux during the first 96h following fall and spring tillage operations (treatments with the same letter are not significantly different from each other, LSD ($p < 0.05$)).

reduce CO₂ losses in this semi-arid region, contributing to the mitigation of green house gases and consequently reducing the negative impact of climate change.

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