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Soil temperature and moisture sensitivities of soil CO_2 efflux before and after tillage in a wheat field of Loess Plateau, China

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Abstract

As a conventional farming practice, tillage has lasted for thousands of years in Loess Plateau, China. Although recent studies show that tillage is a prominent culprit to soil carbon loss in croplands, few studies have investigated the influences of tillage on the responses of soil CO_2 efflux (SCE) to soil temperature and moisture. Using a multi-channel automated CO_2 efflux chamber system, we measured SCE *in situ* continuously before and after the conventional tillage in a rain fed wheat field of Loess Plateau, China. The changes in soil temperature and moisture sensitivities of SCE, denoted by the Q_{10} value and linear regression slope respectively, were compared in the same range of soil temperature and moisture before and after the tillage. The results showed that, after the tillage, SCE increased by 1.2–2.2 times; the soil temperature sensitivity increased by 36.1%–37.5%; and the soil moisture sensitivity increased by 140%–166%. Thus, the tillage-induced increase in SCE might partially be attributed to the increases in temperature and moisture sensitivity of SCE.

Key words: soil CO_2 efflux; Loess Plateau; moisture sensitivity; temperature sensitivity; tillage; wheat field

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Introduction

Soil is the largest carbon pool in terrestrial ecosystems. Release of CO_2 from cropland soils to the atmosphere due to agriculture practice plays an important role in global carbon cycling (Van Oost et al., 2005). It has been estimated the carbon loss from croplands in China was 78 Tg C/yr in 1990s (Li et al., 2003). Recent estimation showed that conversion of cropland practice from conventional tillage to no-tillage will potentially sequester 4.60 Tg C/yr (Lu et al., 2009). As a conventional farming practice, tillage has lasted for thousands of years in China. The reason might be: (1) tillage prevents soil from compacting and so seeds can be sown easily; (2) wheat stubble incorporation after tillage provides more fertilizer for new wheat growing; (3) tillage accelerates nutrient mineralization, prevents weeds and reduces crop diseases; (4) in arid regions, tillage improves rainwater infiltration, and stored in soils for new wheat growing (Hou et al., 2009). However, tillage also stimulates soil organic matter decomposition, releases more CO_2 into the atmosphere, and contributes to global warming (Baker et al., 2007). Measurement of SCE provides a sensitive indication of soil carbon dynamics with high temporal resolution (Grant, 1997) and reveals early signal of tillage-induced changes in soil carbon (Fortin et al., 1996).

Field measurements have shown that tillage increases soil CO_2 efflux (SCE) (Reicosky et al., 1997; Morris et al., 2004; La Scala et al., 2006; Gesch et al., 2007). For example, Calderon et al. (2001) reported that after the tillage, SCE increased by 44% and the increment lasts for 4 days. Reicosky (2002) reported substantial short-term losses of CO_2 immediately after moldboard tillage of mineral soils. La Scala et al. (2006) reported that conventional tillage caused the highest CO_2 emission during almost the whole study period of 4 weeks. Most of these previous studies have been done in relative short term after tillage (Gesch et al., 2007; La Scala et al., 2008) or with less frequent measurements (Curtin et al., 2000; Elder and Lal, 2008; Ussiri and Lal, 2009), due to probably lack of adequate measurement facility. Although there are studies showed that changes in soil temperature and moisture could have a great influence on SCE, less is known about whether the responses of SCE to temperature and soil moisture were changed after tillage. The advent of automated CO_2 efflux

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monitoring facility provides valuable information that is often missed with less frequent manual measurements (Carbone and Vargas, 2008). With the highly frequent and continuous SCE measurements *in situ*, the dynamic responses of SCE around tillage may be better documented and revealed.

In this study, we measured SCE continuously using 3 chambers of a multi-channel automated chamber system in a period of 74 days around the tillage in a wheat field of Loess Plateau, China. Our aims were to document and reveal the changes in SCE before and after tillage and quantify the effects of tillage on the responses of temperature and soil moisture sensitivities of SCE.

1 Materials and methods

1.1 Site description

This study was conducted at Changwu Agro-Ecological Experimental Station of Chinese Academy of Sciences located in the south of central Loess Plateau (35°12′N, 107°40′E). The elevation is approximately 1200 m above sea level. The climate is classified as semi-arid continental monsoon. The mean annual precipitation and temperature are 584 mm and 9.1°C, respectively, and about more than 60% rainfall concentrated from June to September which overlaps with high temperature of the year. The soil is moderately loamy Heilu soil with much porous and high water holding capacity, and subjected to moisture deficit frequently. Soil pH is about 8.4 and soil organic matter content is about 3%. Wheat field is one of the major traditional land use types and occupies 44% of the cultivated area in the Loess Plateau (Jin et al., 2007).

1.2 Farming practice

The winter wheat in the study field was sown in September, 2006, and harvested on Julian day of 166, 2007 (June 15, 2007). After harvesting, the wheat field was left stubble covered. On Julian day of 204 (July 23, 2007), 37 days after the wheat harvesting, the land was tilled up to a depth of 20 cm by moldboard plow as a normal farming practice. The stubble was incorporated into soil by the tillage. Then the field was in fallow till next wheat sowing.

1.3 Automated chamber system

SCE was measured *in situ* continuously by a multi-channel automated chamber system (Zhang et al., 2007, Fig. 1) improved from the methods introduced by Goulden and Crill (1997), Liang et al. (2003) and Bubier et al. (2002).

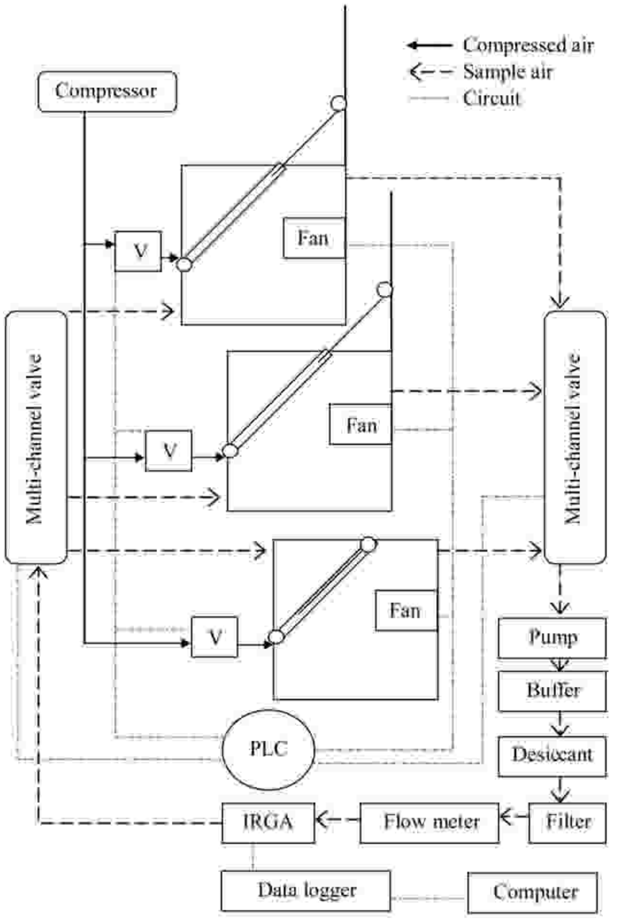

Fig. 1 Diagram of the multi-channel automated chamber system for SCE measurement. PLC: programmable logic controller; V: solenoid valve; IRGA: inferred gas analyzer.

The measurement chambers (50 cm × 50 cm × 50 cm, length × width × height) had walls made from transparent PVC glued and fixed to the aluminum alloy and had opaque lids hinged at the sidewalls. The high-density rubber gaskets were glued to the upper edge of the chambers for tight closing. A small fan within each chamber was used for mixing the air when the lid was closed. A tube of 1.5 m in length and 4 mm in inner diameters was inserted through the lid of each chamber to maintain the pressure inside the chamber near the ambient air pressure when chamber was closed (Griffis et al., 2004). A cylinder was positioned within each chamber and pneumatically driven by high-pressured air from a compressor to control the opening and closing of chamber lid (Liang et al., 2003). IRGA (Li-820, LiCor Inc., USA) was used to monitor the CO_2 concentration change within the chamber by the dynamic close method. Air sample was pumped from one chamber which was closed for measuring to pass through a multi-channel valve, the buffer tube, the desiccant tube, the filter, and the flow controller into the IRGA for CO_2 concentration measurement, then return to the chamber. A programmable logical controller (PLC, Master-K120S, LG, Korea) was employed to control a series of solenoid valves for opening and closing the target chamber, and air gas sample from target chamber. Each chamber was closed for 3 min (Drewitt et al., 2002) for the measurement. The flow rate was controlled at 1 L/min. The CO_2 concentrations were monitored continuously by the IRGA and recorded at the interval of 10 sec by a data logger (CR10X, Campbell Scientific Inc., USA). The T-type thermocouple and ECH_2O (EC-5, Decagon Device Inc., USA) sensor was used to measure the soil temperature and moisture at the depth of 10 cm near each chamber. Air temperature inside chamber was measured with T-type thermocouple along with SCE measurement. Air temperature at 1.5 m above the soil surface was measured with HMP45C (Campbell Scientific Inc., USA). The temperature and soil moisture were recorded at an interval of 3 min in the data logger (CR10X). The daily rainfall and hourly air pressure data were derived from Changwu Agro-Ecological Experiment Station of Chinese Academy of Sciences, only 50 m away from the experimental site.

1.4 Measurement of SCE

Three replicate chambers were inserted 5 cm into the soils on Julian day of 166 after wheat harvesting and kept *in situ* till to the end of the measurement. The distance from one chamber to another was 4–5 m. The chambers were taken off temporarily before tillage on Julian day 204 and immediately inserted into the same plot after tillage to ensure that the measurement position was not altered and the continuity of the measurement. SCE measurement started on Julian day 166, 2007, and ended on Julian day 240, covering the fallow period.

1.5 Data processing

Data were downloaded every day from the data logger to computer. The CO_2 concentration data from 1 min after chamber closed to 20 sec before the chamber opening were used to calculate the change in CO_2 concentration, which is the slope of the linear regression of CO_2 concentration and the time when the correlation coefficient is larger than 0.95. SCE was calculated using Eq. (1) (Davidson et al., 1998; Steduto et al., 2002; Drewitt et al., 2002):

$$R = \left(\frac{\mathrm{d}c}{\mathrm{d}t}\right) \times \left(\frac{V \times P}{S \times r \times T}\right) \tag{1}$$

where, R (μmol/(m^2·sec)) is the SCE; c (μmol/mol) is the mole fraction of the CO_2; $\mathrm{d}c/\mathrm{d}t$ (ppm/sec) is the change rate in CO_2 concentration; V (m^3) is the volume of the chamber; S (m^2) is the ground surface area enclosed by the chamber; P (kPa) is the atmospheric pressure inside the chamber; r (8.3×10^{-3}(m^3·kPa)/(mol·K)) is the universal gas constant; T (absolute air temperature) is the air temperature inside the chamber.

The sensitivity of SCE to soil temperature was assessed using Q_{10} derived from the exponential function (Davidson et al., 1998; Buchmann, 2000; Xu and Qi, 2001; Luo et al., 2001; Hui and Luo, 2004):

$$R = a \times \mathrm{e}^{b \times T} \tag{2}$$

$$Q_{10} = \mathrm{e}^{10 \times b} \tag{3}$$

where, T (°C) is the soil temperature; a and b are parameters to be estimated by fitting Eq. (2) to field measured data.

The sensitivity of SCE to soil moisture was assessed by the slope (c) of the linear regression of SCE to soil moisture (Smith, 2005):

$$R = c \times W + d \tag{4}$$

where, W (m^3/m^3) is the soil moisture; c and d are parameters.

Previous investigations have demonstrated that soil temperature and moisture sensitivities of SCE are strongly confounded by the changes in soil temperature and moisture themselves (Borken et al., 2003; Harper et al., 2005; Sponseller, 2007). In undisturbed ecosystems, temperature and moisture are most crucial because both can account for 69%–95% of the temporal variability of SCE (Davidson et al., 1998; Xu and Qi, 2001; Tufekcioglu et al., 2001). In order to identify the tillage effect on SCE, we excluded the confounding effects of temperature and moisture by comparing SCE measured under similar soil temperature and moisture conditions. The common ranges of soil temperature and soil moisture before and after the tillage were determined to be 20–30°C for soil temperature and 0.24–0.30 m^3/m^3 for soil moisture in this study. All data were grouped into two groups according to soil temperature (i.e., 20–25°C and 25–30°C and three groups according to soil moisture (i.e., 0.24–0.26 m^3/m^3, 0.26–0.28 m^3/m^3, and 0.28–0.30 m^3/m^3). For each group, soil temperature and moisture, SCE and its soil temperature and moisture sensitivities were calculated.

The Student's *t*-test was conducted to test the differences in temperature, soil moisture and SCE before and after tillage using SPSS software (v13.0, SPSS Inc, USA). To assess soil temperature and soil moisture sensitivities, the exponential and linear regressions of SCE with soil moisture and temperature were established, respectively, using Sigma Plot software (v10.0, Systat Software Inc., USA).

2 Results

2.1 Meteorological factors before and after the tillage

There was no significant difference in air temperature before and after tillage ($P > 0.05$, Fig. 2). Rainfall after the tillage (117.9 mm) was 19.21% more than that before the tillage (98.9 mm). The mean soil temperature and moisture were significantly higher after the tillage than those before tillage ($P < 0.001$, Fig. 3). The mean soil temperature at 10 cm depth was (22.33 ± 2.63)°C before the tillage and (23.58 ± 3.67)°C after tillage. The mean soil moisture at 10 cm depth was (0.22 ± 0.05) m^3/m^3 before tillage and (0.26 ± 0.05) m^3/m^3 after tillage. The diurnal variation in soil temperature was also higher after the tillage than before the tillage (Fig. 3a).

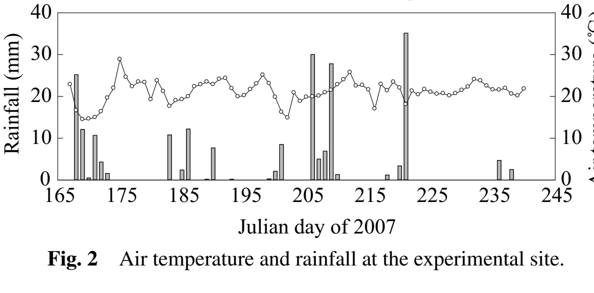

Fig. 2 Air temperature and rainfall at the experimental site.

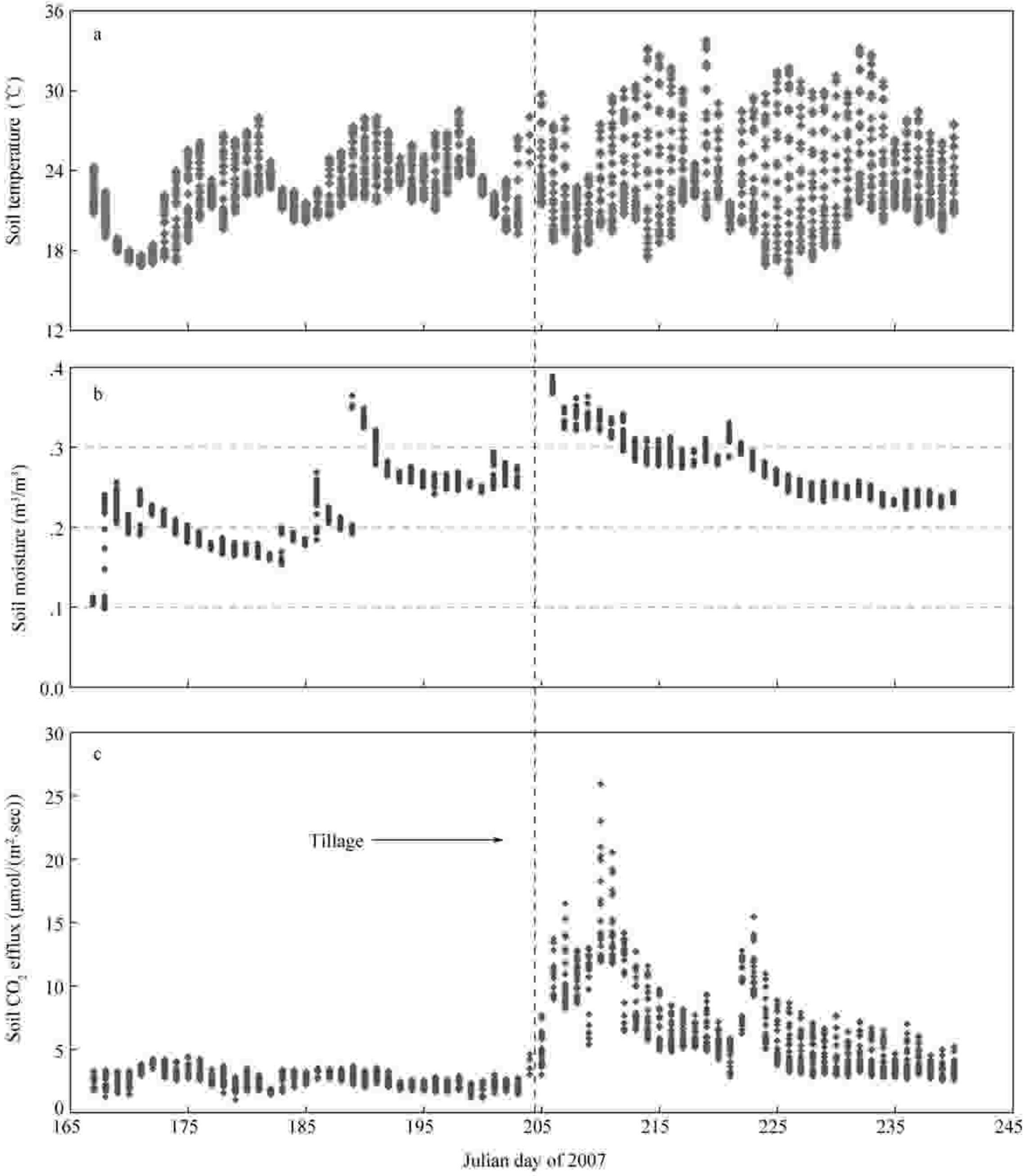

Fig. 3 Soil temperature at 10 cm depth (a), soil moisture at 10 cm depth (b), and SCE (c) before and after the tillage in the wheat field. Dashed line designates the time when the tillage was taken.

2.2 SCE before and after the tillage

SCE significantly increased after the tillage, especially immediately after rainfalls (Fig. 3b). The mean SCE increased from (2.56 ± 0.66) μmol/(m^2·sec) before the tillage to (6.73 ± 3.61) μmol/(m^2·sec) after the tillage ($P < 0.001$), with an increment of 2.6 times. The significantly higher SCE after the tillage lasted over 37 days (Fig. 3). By comparing SCE measured before and after the tillage in the same ranges of soil temperature and moisture, the CO_2 efflux increased by 1.2–2.2 times (Table 1).

Table 1 SCE averaged for each ranges of soil temperature and moisture before and after the tillage

	Soil moisture (m^3/m^3)	SCE (μmol/(m^2·sec))	
		20–25°C	25–30°C
Before tillage	0.24–0.26	1.90 (0.18)	2.18 (0.22)
	0.26–0.28	2.25 (0.33)	2.49 (0.22)
	0.28–0.30	3.09 (0.24)	3.05 (0.42)
After tillage	0.24–0.26	4.16 (0.91)	5.34 (1.12)
	0.26–0.28	5.69 (0.66)	7.87 (1.22)
	0.28–0.30	6.81 (0.96)	7.51 (1.31)
Increment (%)	0.24–0.26	118	145
	0.26–0.28	153	216
	0.28–0.30	121	146

Numbers in parentheses represent standard deviations.

2.3 Temperature sensitivity before and after the tillage

The exponential relationships between SCE and soil temperature were significant in each of the three soil

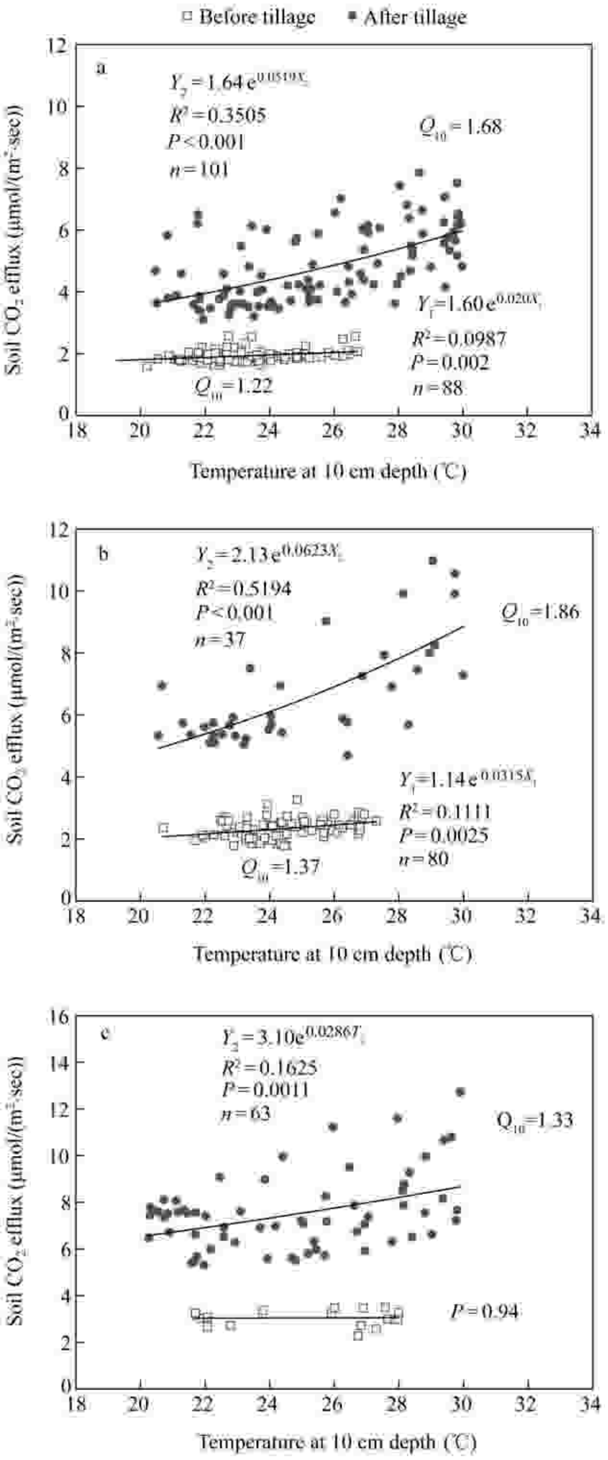

Fig. 4 Exponential relationships between SCE and soil temperature before and after the tillage within soil moisture ranges of 0.24–0.26 m^3/m^3 (a), 0.26–0.28 m^3/m^3 (b), and 0.28–0.30 m^3/m^3 (c).

moisture groups (0.24–0.26 m^3/m^3, 0.26–0.28 m^3/m^3 and 0.28–0.30 m^3/m^3) ($P < 0.001$) both before and after the tillage except in the group of 0.28–0.30 m^3/m^3 before the tillage (Fig. 4). The soil temperature sensitivity (Q_{10}) was 1.22–1.37 before the tillage and 1.33–1.86 after the tillage. Q_{10} increased 36.1%–37.5% after the tillage.

2.4 Soil moisture sensitivity before and after the tillage

There were significant linear relationships ($P < 0.001$) between SCE and soil moisture in each soil temperature group (20–25°C and 25–30°C both before and after the tillage (Fig. 5). The soil moisture sensitivity of CO_2 efflux (i.e., the slope of the regression of CO_2 efflux to moisture) after the tillage was remarkably higher (140%–160%) than those before the tillage in each soil temperature ranges, increased from 25.29–26.17 before the tillage to 62.70–67.26 after the tillage (Fig. 5).

3 Discussion

3.1 Tillage's effect upon SCE

Using an automated chamber system, we measured SCE *in situ* continuously before and after the tillage. We found that SCE increased by 1.1–2.2 times (Table 1) after the tillage. This is consistent to previous reports. For example, the annual total SCE in wheat cultivation enhanced 20%–23% due to tillage in 1995–1996 (Curtin et al., 2000). The SCE increased by 160% due to conventional tillage in a sugar cane field in Brazil (La Scala et al., 2006). On average, the conventional tillage resulted in an increase of 130%–500% of SCE in Turkey (Akbolat et al., 2009). Till-induced increments in mean SCE in our study were close to these measured in short-term experiments during summer or fall season but markedly higher than those measured over a year, because our experiment was conducted at the peak period of SCE of the year with high temperature and precipitation.

The mechanism underlying the effect of tillage on SCE is complicated. Tillage could change soil physical factors, such as soil temperature, soil moisture, O_2 concentration, the contact of soil microbes with substrate, and substrate distribution. In this study, soil temperature and moisture increased significantly after the tillage, although the air temperature and rainfall did not differ much. The reason may be that the tillage-loosed soil was favorable to heat exchange and rainfall infiltration. In the semi-arid Loess Plateau, conventional tillage has been considered as a useful management measure to store soil water in fall to meet wheat growth in the next drought spring (Hou et al., 2009). Tillage also could disrupt soil aggregate and transferring labile or fresh organic matter once protected by aggregates to unprotected readily decomposable organic matter exposing to microbial attack (Beare et al., 1994; De Gryze et al., 2006; Grandy and Robertson, 2007; La Scala et al., 2008).

Change in soil organic matter could also contribute to the variation in SCE. While there was no additional organic matter input to cropland ecosystems during our measurements, the tillage practice changed the distribution of organic matter. Tillage incorporated crop residue into soils and improved soil aeration condition and diffusion of gases into soils (Reicosky, 1997). As a result, we observed the higher SCE rate after the tillage (Beare et al., 1994; Kladivko, 2001; Calderon et al., 2001). The lower SCE before the tillage might be due to slower decomposition

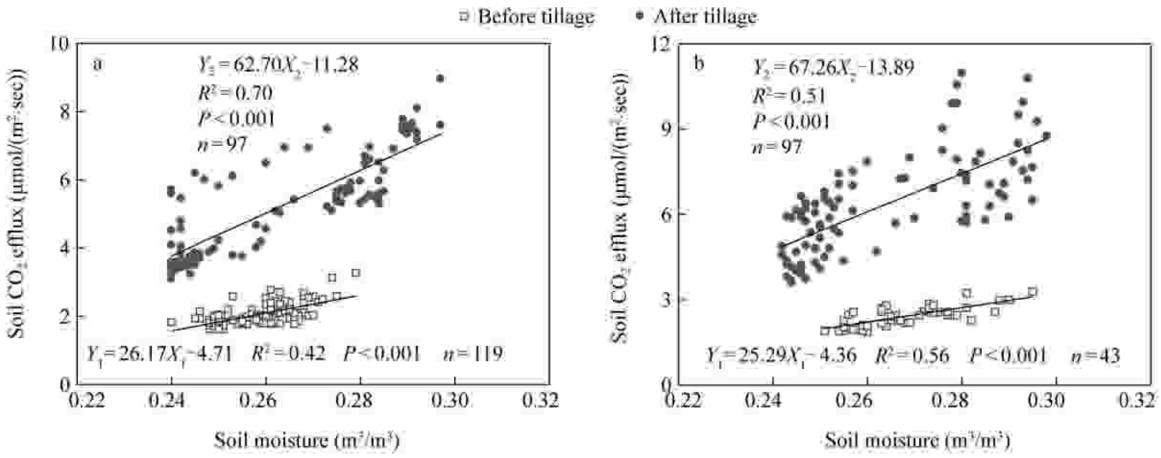

Fig. 5 Linear relationships between SCE and soil moisture at 10 cm depth before and after the tillage within soil temperature ranges of 20–25°C (a) and 25–30°C (b).

of crop residues placed on the soil surface than when they were incorporated into mineral soils after the tillage (Curtin et al., 2000).

3.2 Temperature sensitivity of SCE

In the three equal soil moisture stages (0.24–0.26 m^3/m^3, 0.26–0.28 m^3/m^3, 0.28–0.30 m^3/m^3), and in the same temperature range (20–30°C), we found Q_{10} after tillage increased by 36.1%–37.5% compared to that before the tillage (Fig. 4). The Q_{10} was in the range of 1.22–1.86, smaller than 2 as frequently reported in other studies (Wan and Luo, 2003; Xu and Qi, 2001). This may be due to the relatively higher temperature during our measurements. SCE was measured around the tillage when the temperature was the highest of the year and the soil became less sensitive to temperature. Bekku et al. (2003) previously reported that the Q_{10} in the temperate soil decreased with increasing incubation temperature: from 2.8 in soils incubated at 8°C to 2.5 at 12°C and 2.0 at 16°C.

There were only a few studies that focused on Q_{10} changes due to tillage in spite of its great significance in carbon models. For example, La Scala et al. (2005) studied the SCE after rotary tillage of a tropical soil and evaluated their temperature sensitivity using linear model. They found that the slopes of the linear models increased with rotation speed of blade. Unlike other studies, we compared Q_{10} before and after the tillage under the same soil moisture and soil temperature ranges to avoid the influences of soil temperature and moisture (Lloyd and Taylor, 1994; Davidson et al., 1998; Conant et al., 2004). The result indicates that, in addition to soil temperature and moisture, tillage might exert significant effect upon Q_{10} of SCE. The increases in Q_{10} after the tillage were probably due to that tillage incorporated residue into soil and increased soil carbon substrate. Q_{10} is partially depends on substrate available (Davidson and Janssens, 2006). Tillage exposed organic carbon to aeration environment, changed soil microbial community structure and function (Jackson et al., 2003), and released more soil CO$_2$ from loosed soil (Beare et al., 1994; Kladivko, 2001) which might also influence Q_{10} of SCE.

3.3 Soil moisture sensitivity of SCE

By grouping data into two temperature ranges (i.e., 20–25°C and 25–30°C), in the equal soil moisture range (0.24–0.30 m^3/m^3), we found that soil moisture sensitivity to SCE increased after the tillage (Fig. 5). The increases were probably due to the similar reasons that the tillage increased soil substrate, and changed microbial community and environmental conditions, as described above. In a similar experiment, the SCE sensitivity to soil moisture enhanced about 280% due to tillage in a tropical sugar cane ecosystem (La Scala et al., 2006) which was higher than those in our study (140%–160%). Differences in soil moisture state might contribute to this different effect of tillage upon soil moisture sensitivity (Conant et al., 2004). In addition to this, tillage method and strength, soil temperature state (Smith, 2005) might also influence the soil moisture sensitivity. Higher temperature in the tropical region might amplify the effect of tillage upon soil moisture sensitivity of SCE. In Loess Plateau of China, tillage usually occurs in wet season. The increasing soil moisture sensitivity due to tillage might exert great influence on SCE.

4 Conclusions

Using a multi-channel automated CO$_2$ efflux chamber system, we measured SCE continuously in a wheat field of Loess Plateau, China around the tillage to assess the tillage effect. The SCE increased remarkably and the enhancements lasted over 35 days of the measurement. The soil temperature and moisture sensitivities of SCE also increased after tillage. We suggested that the enhancements in SCE might be partially related to the increases in temperature and soil moisture sensitivities of SCE. The relatively higher soil temperature and moisture accompanied by enhanced temperature and moisture sensitivities would release more CO$_2$ from soils after the tillage, intensify the global warming. Tillage is still a farming practice widely used in Loess Plateau, China and overlaps with hot and wet summer. From this point of view, the conventional tillage practice should be reevaluated.

Acknowledgments

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