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Original Research Paper

Soil Respiration and its Relationship to Environmental Factors in Three Land Uses on the Loess Tableland

Xiaoyang Han*(**), Wenzhao Liu*†, Fengru Fang* and Jie Chen***

*State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources/Northwest A&F University, Yangling, Shaanxi, 712100, China

**University of Chinese Academy of Sciences, Beijing 100049, China

***École de technologie supérieure, Université du Québec, 1100, rue Notre-Dame Ouest, Montreal, QC., H3C 1K3, Canada

†Corresponding author: Wenzhao Liu

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ABSTRACT

Investigating the contribution of different land use types to the carbon cycle of terrestrial ecosystems is of considerable importance in studying global climate change. The objective of this study is to determine the temporal variation of soil respiration rates in different land uses (maize, wheat stubble, and bare land) and their responses to environmental factors for the Loess Tableland, using an improved multi-channel automatic flux chamber system. Results showed that the soil respiration rate indicates a clear diurnal and seasonal variations. The mean soil carbon emission rates were 0.94, 1.94 and 2.38 $gC{\cdot}m^{-2}{\cdot}d^{-1}$ in bare land, wheat stubble field, and maize field, respectively. The determination coefficient of soil surface temperature on the diurnal soil respiration rate was more significant than that of deeper layers. The Q_{10} value was used to represent the temperature sensitivity of soil respiration in three different land uses, soil respiration in the maize field showed the largest temperature sensitivity. The soil respiration was found to increase exponentially with the increase in air temperature, whereas the relationship between soil respiration and soil moisture was quadratic. The trend of rainfall-affected soil respiration after the sudden rain and continuous light rain showed large differences, meanwhile, a clear difference in the sensitivity of soil respiration to rainfall exists for the different land uses.

INTRODUCTION

The increase in atmospheric carbon dioxide (CO_2) concentration caused by global climate change has elicited universal concern, especially on the CO_2 exchange flux between terrestrial ecosystems and the atmosphere. The terrestrial ecosystem is important in the global carbon cycle, and soil respiration and gross photosynthesis are the major pathways of carbon exchange between the terrestrial ecosystem and the atmosphere (Zhang et al. 2011). Soil respiration is often determined by measuring the soil surface CO_2 flux. Several methods have been developed to measure the soil surface CO_2 flux, which is the major source of uncertainty for the global carbon cycle (Raich & Schlesinger 1992). Soil respiration is a combined flux of roots and microorganisms from different soil depths, which can be affected by several factors and their interactions (Buchmann 2000). Identifying the factors that control soil CO_2 emissions and their effects on emission rates is necessary in assessing the potential impacts of environmental change (Raich & Tufekcioglu 2000).

Soil temperature and soil moisture are two main factors affecting soil respiration rates (Raich & Schlesinger 1992, Davidson et al. 1998). The effect of soil moisture is not significant for normal soil moisture conditions. However, such effect becomes more important as drought is aggravated when microbial activities are curbed by physiological stress (Davidson et al. 1998, Lee et al. 2004) and, at times of near saturation caused by rainstorms, when oxygen is limited (Moncrieff & Fang 1999). Considerable literature has focused on the response of soil respiration to wet conditions. However, most studies were conducted under a laboratory environment (Schnurer et al. 1986, Borken et al. 2002), and only a few were reported under field conditions (Liu et al. 2002, Lee et al. 2004). The major biome type is also a determinant factor for the soil respiration rate. Modifying the responses of soils to the environment is possible with changes in vegetation (Raich & Schlesinger 1992, Raich & Tufekcioglu 2000). Moreover, vegetation may influence the soil microclimate and structure, the quantity of detritus supplied to the soil, the quality of that detritus, and the overall root respiration rate.

The Loess tableland located in the central and southern regions of the Loess Plateau is an important crop production base in northwest China. In recent years, agricultural and industrial restructuring has resulted in a variety of land use types, with the exception of traditional food crops such as winter wheat and spring maize. Soil respiration in different land use types may be different. Accordingly, the objective of this study is to investigate the temporal variation of soil respiration rates in different land uses and their responses to environmental factors, which is helpful in revealing the varying characteristics of farmland soil respiration in the Loess tableland area and providing certain references for regional- and large-scale carbon research. Soil respirations of three different land uses (maize, wheat stubble, and bare land) were measured continuously using an improved multi-channel automatic flux chamber system. Responses of soil respiration to environmental factors during rainfall were also studied.

MATERIALS AND METHODS

Site description: This study was conducted at the Changwu Agro-Ecological Experiment Station of the Chinese Academy of Sciences on the Loess Plateau of China (35°12' N, 107°40' E). The elevation is approximately 1,200 m above the sea level. The climate is controlled by the subhumid continental monsoon, the annual mean temperature is 9.1°C, with a mean annual precipitation of 584mm and an annual mean potential evaporation of 980mm (Han et al. 2015). The Loess tableland is a typical rain-fed agricultural area. As such, rainwater is the main water resource for the crop growth. The soils are Cumuli-Ustic Isohumosols (Gong et al. 2007), which is very porous and has a high water holding capacity. However, this soil type suffers from moisture deficit under uneven rainfall and high evaporation conditions (Table 1). The soil pH value is approximately 8.4, with soil organic matter content of approximately 3%.

Methodology: The soil respiration was measured in three experimental plots with different land uses (maize, wheat stubble, and bare land) using a multi-channel automated chamber system (Fig. 1) with three replications for each land use type. The area of each plot is 100 m^2, with a side length of 10 m. The chamber was made of transparent PVC, with length, width, and height of 50, 50, and 50 cm, respectively. Two small fans were mounted inside to mix the air in the chamber when the lid was closed.

A programmable logical controller (PLC, Master-K120S, LG, Korea) was used to control a series of solenoid valves (nine chambers) to drive the opening and closing of the target chamber, and circulate gas samples to and from the target chamber. A cylinder driven by high pressure from a compressor to open and close the chamber lid was positioned in each chamber. Soil respiration, temperature, and soil water content were measured with an interval of 1 h. However, the measurement needed to be finished within 3 min when the chamber lid was closed. Air sample was pumped from the closed chamber into the IRGA (infrared gas analyzer, Li-820, Li-Cor, Lincoln, NE) to measure the CO_2 concentration. The flow rate was controlled at 0.8-1.2 $L \cdot min^{-1}$. Data were recorded using a data logger (CR1000, Campbell Scientific, Logan, UT) at an interval of 10s within the allotted 3 min.

A portable moisture meter was used to measure soil moisture in the chamber at a depth of 10cm. The temperature sensor was used to measure soil temperature at depths of 0, 10, and 20cm, and air temperature within the chamber was measured using a copper-constantan thermocouple. The ambient air temperature, daily rainfall, and hourly air pressure data were derived from meteorological data of the experiment station.

Data analysis: Data were downloaded every day from the data logger. The soil respiration was calculated using equation (1) (Davidson et al. 1998):

$$A = \frac{dc}{dt}\frac{V}{S}\frac{P}{RT} \quad ...(1)$$

Where, A is soil respiration rate (CO_2 flux in a certain area during a period of time, $\mu mol \cdot m^{-2} \cdot s^{-1}$); dc/dt is change rate in CO_2 concentrations; V is volume of the chamber (m^3); S is the ground surface area enclosed by the chamber (m^2); P is atmospheric pressure inside the chamber (kPa); R is the universal gas constant (8.3144×10^{-3} $kPa \cdot m^3 \cdot mol^{-1} \cdot K^{-1}$); and T is air temperature inside the chamber (K).

Diurnal and seasonal variations of the soil respiration were analysed using two different datasets. The diurnal variation was analysed based on the hourly data, while the seasonal variation was based on the daily data. The correlation between soil respiration and environmental factors (temperature and soil moisture) was analysed using the SPSS19.0 software (IBM SPSS Statistics, USA).

Table 1: The distribution of rainfall and ET_0 in each month of 2011.

Time period	1	2	3	4	5	6	7	8	9	10	11	12	Annual
Precipitation, mm	5	12.2	14	7.4	69.2	29.8	112	78.2	198.2	42.8	72.4	3	644.2
ET_0, mm	19.3	39.9	71.3	128.7	130.3	147.4	136.7	104.5	65.1	54.7	25.9	22	945.7

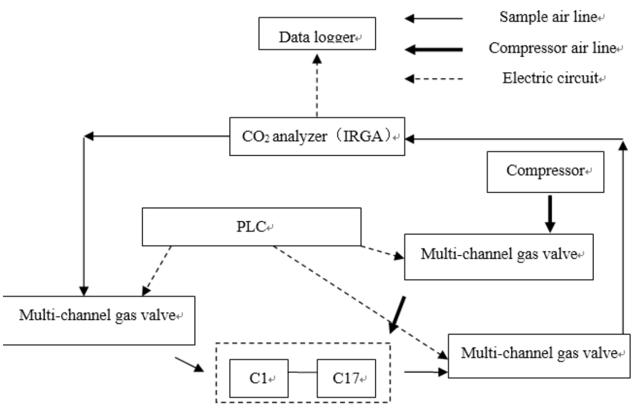

Fig. 1: The automated multi-chamber system.

RESULTS

Seasonal variations of microclimate and soil respiration: Soil respiration of the three land uses was observed during the period between July 1 and September 28, 2011. Environmental conditions varied widely during the measurement period (Fig. 2a, b, c, d). The mean soil surface temperature in bare land, wheat stubble field, and maize field were 21.7, 21.2 and 19.7°C, respectively, and ranging from a maximum of 31.5, 27.6 and 25.5°C in July to a minimum of 9.0, 11.0 and 9.6°C, respectively, in September. The mean soil moisture at 10 cm depth in the bare land, wheat stubble field, and maize field were 13.9%, 12.3% and 14.2%, respectively. The total precipitation during the measurement period was 388.4mm. The seasonal variation of soil respiration during this period was consistent with the temporal variation in the soil temperature (Fig. 2e).

The soil CO_2 emission rates in bare land, wheat stubble field, and maize field were 0.07, 1.10, and 0.76g $C \cdot m^{-2} \cdot d^{-1}$, respectively, and with maximum rates of 1.30, 3.68, and 4.86g $C \cdot m^{-2} \cdot d^{-1}$, respectively. The range of soil respiration changes in the bare land was narrower than that in the other two land uses.

Precipitation on the Loess tableland mainly occurred in July, August, and September in 2011 (Fig. 2d). Rainfall during this period caused several sharp declines and rebounds in soil respiration (Fig. 2e). The most obvious one occurred on July 28, when heavy rain (32.8 $mm \cdot d^{-1}$) occurred after 10 days without effective precipitation. The soil carbon emission in the three land uses quickly declined from 0.95, 1.74 and 3.40g $C \cdot m^{-2} \cdot d^{-1}$ to 0.40, 1.35 and 1.55g $C \cdot m^{-2} \cdot d^{-1}$, then rose sharply on July 30, after the rain, to 1.08, 3.64 and 4.86g $C \cdot m^{-2} \cdot d^{-1}$.

The total carbon emission in the bare land, wheat stubble field, and maize field during the entire period were 84.24, 174.76 and 214.16g $C \cdot m^{-2}$, respectively, with the average soil respiration rate of 0.94, 1.94 and 2.38g $C \cdot m^{-2} \cdot d^{-1}$, respectively. The daily average carbon emissions of July, August and September for the three land uses showed considerable differences (Fig. 3). The standard deviation of daily carbon emission in the maize field was the highest, this may be due to vigorous root growth of maize during this stage.

Diurnal variation of soil respiration and soil temperature: This study showed that soil respiration in the bare land, wheat stubble field, and maize field were more significantly determined by the soil surface temperature (Ts-0) than 10 and 20 cm-soil temperature at the 0.01 level (Table 2). Thus, soil surface temperature was used to show the impacts of soil temperature on diurnal variations of soil respiration.

As the soil temperature varied with weather conditions, the diurnal variation of the soil respiration under different weather conditions also showed a large difference. The average soil respiration rates of typical sunny days (cloud cover less than 20%) and cloudy days (cloud cover more than 80%) in three months were selected to show the diurnal variations of soil respiration in the three land uses (Fig. 4).

The pattern of soil respiration rate was asymmetric on sunny days. The magnitude of the day and night change was large, with the minimum value occurring at about 3:00 to 5:00, and the maximum value occurring at about 13:00 to 15:00. However, the condition became more complex on cloudy days. The soil respiration rate in the bare land was consistently lower than that of the other two land uses, indicating a dominant control of root-associated soil respiration.

Temperature sensitivity of soil respiration: Generally, soil respiration is positively correlated with temperature. An exponential curve was used to investigate the relationship between soil respiration and soil temperature for the three land uses.

$$SR = \alpha e^{\beta T} \quad ...(2)$$

Where SR is the soil respiration rate ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$), T is the soil temperature (°C), and α and β are parameters. Q_{10} value with the form of:

$$Q_{10} = e^{10\beta} \quad ...(3)$$

was used to represent the corresponding multiples of soil respiration increase when the soil temperature is increased by every 10°C, which is a sign of temperature sensitivity for soil respiration.

The soil respiration in the maize field showed the largest temperature sensitivity, followed by the bare land, while the smallest temperature sensitivity was observed in the wheat stubble field (Table 3). Moreover, the temperature sensitivity of soil respiration increased with the increase of soil depth.

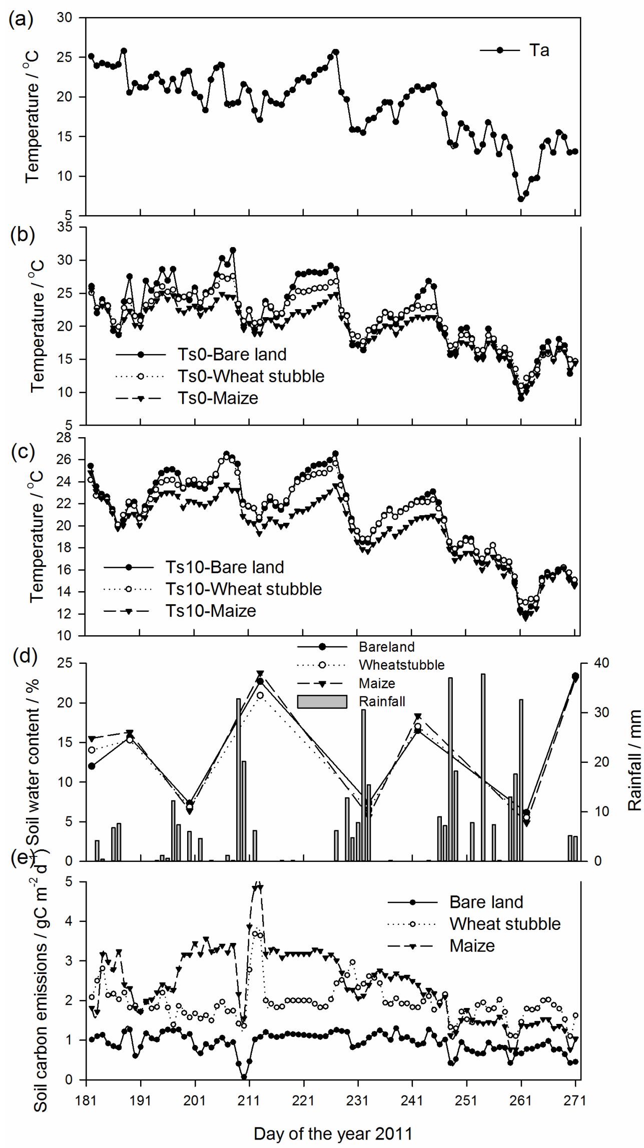

Fig. 2: Seasonal variation of (a) air temperature, (b) soil surface temperature, (c) soil temperature at 10cm depth, (d) precipitation and soil water content (SWC) at 10cm depth and (e) soil carbon emission (from CO_2) in three land uses.

Table 2: Determination coefficient of soil temperature on diurnal soil respiration rates.

Land use	Ts-0 (°C)	Ts-10 (°C)	Ts-20 (°C)
Bare land	0.574**	0.382**	0.380**
Maize	0.429**	0.293**	0.255**
Wheat stubble	0.617**	0.601**	0.591**

Note: Ts- Soil temperature at 0, 10 and 20cm depth, ** represent significant at 0.01 level (2-tailed)

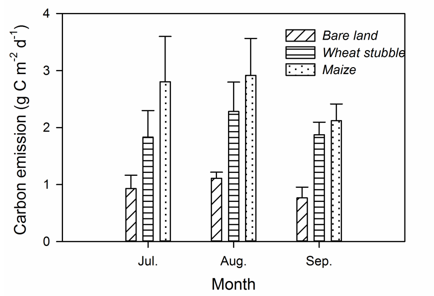

Fig. 3: Daily averaged carbon emission of three land uses in July, August and September.

Table 3: The Q_{10} values of diurnal soil respiration in three land uses.

Q_{10}	Bare land	Wheat stubble	Maize
Ts-0 (°C)	1.26	1.24	1.44
Ts-10 (°C)	1.53	1.31	2.17
Ts-20 (°C)	1.83	1.42	2.58

Note: Ts - Soil temperature at 0, 10 and 20cm depth.

Effects of soil moisture on soil carbon emission: Soil respiration was found to increase exponentially with an increase in temperature, whereas, the influence of soil moisture on soil respiration was more complicated. The correlation between soil carbon emission and soil moisture indicated quadratic patterns on certain days (Fig. 5). When the soil moisture was under a certain value of 20%, the increase in soil moisture could enhance soil respiration. However, soil respiration would be inhibited once the soil moisture was greater than 20%.

Response of soil respiration rates to rain: The instantaneous soil respiration may be affected by a sudden rainfall, as rain can quickly change soil water conditions (Lee et al. 2004). As mentioned previously, the diurnal variation of soil respiration on a sunny day was unimodal, with the peak occurring at approximately 13:00 to 15:00. However, the rain completely changed this trend.

Typical rainfall events on July 28 (Julian day 209 of 2011) and September 5 (Julian day 248 of 2011) were selected to show the effect of sudden rainfall on instantaneous soil respiration (Fig. 6). The total precipitations for the two days were 32.8 mm and 37.8 mm, respectively. The maximum rainfall intensity on September 5 was 6.2 mm·h^{-1}, which was much smaller than the heavy rainfall on July 28 (11.4 mm·h^{-1}). The trend of rainfall-affected soil respiration after the sudden rain and continuous light rain showed large differences. On July 28, at 9:00, the soil respiration rate in the bare land, wheat stubble field, and maize field decreased from 0.76, 1.45, and 3.02 µmol CO_2·m^{-2}·s^{-1}, respectively, to 0.08, 1.08, and 1.27 µmol CO_2·m^{-2}·s^{-1} at 14:00 (the max rainfall 11.4 mm·h^{-1}). The soil respiration rate then rose gradually to

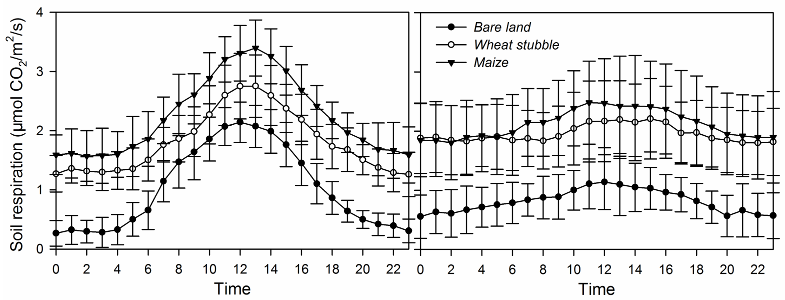

Fig. 4: Diurnal patterns of soil respiration on typical days. Data of soil respiration rate represent means ± standard error (n=24).

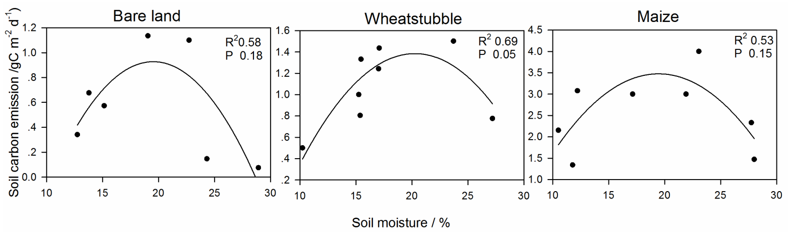

Fig. 5: The influence of soil water content on soil respiration.

2.10, 5.71 and 6.19 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ on July 30 after the rain (Fig. 6a). However, the variation amplitude of soil respiration on September 5 was smaller (Fig. 6b). The soil respiration of the three land uses declined from 0.78, 1.88, and 2.09 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ to 0.29, 0.08, and 1.50 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$, then returned to the pre-rain rate shortly after the rain stopped. Meanwhile, a clear difference in the sensitivity of soil respiration to rainfall exists for the different land uses, ranked in descending order of the wheat stubble field, maize field, and bare land.

DISCUSSION

Temporal variations of soil respiration in different land uses: During the observation, the daily dynamics of soil respiration was asymmetric, which was consistent with the pattern of the diurnal variation in the forest (Davidson et al. 1998, Xu & Qi 2001), grassland (Liu et al. 2002, Cao et al. 2004, Jia et al. 2005), farmland (Han et al. 2006, Gao et al. 2011, Zhang et al. 2011), and wetland ecosystems (Li et al. 2003). The ranges of soil respiration rates in the bare land (0.11 to 3.14 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$), wheat stubble field (0.18 to 5.71 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$), and maize field (0.51 to 6.19 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$) also showed clear differences. Gao et al. (2011) determined a range of 0.29 to 1.82 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ for bare field on the Loess tableland measured by a Li-8100. The soil respiration of the maize field in northeast China ranged from 1.31 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ to 4.77 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$, as reported by Han et al. (2007), which were smaller than those of this study.

Seasonal dynamics of soil carbon emission herein were consistent with those of other studies under temperate climates, such as a mixed hardwood forest in Harvard Forest in the US and in European beech, Norway spruce (Davidson et al. 1998), and Scots pine forests in Germany (Borken et al. 2002). The soil respiration in the bare land studied herein appears to have a smaller seasonal variation than that of the wheat stubble and maize fields, which may be due to the seasonal growth of the root system. Raich & Schlesinger (1992) reported a positive effect of precipitation and air temperature on soil respiration for all climate regions. However, the variation of soil respiration rates in the different land uses within climate regions was very large.

Relationships among soil respiration, soil temperature, and soil moisture: Soil temperature, soil moisture, and their interaction largely control the temporal and spatial variations in soil respiration during the growing season (Xu & Qi 2001, Han et al. 2007). In this study, correlations among soil respiration and soil temperature, and soil moisture in the three land uses were different. Soil respiration in the three land uses were significantly correlated with soil temperature (0, 10, and 20 cm) at the $P = 0.01$ level, and the soil surface temperature could explain 57%, 43%, and 62% of diurnal variation in the soil respiration for bare land, wheat stubble field, and maize field, respectively. However, in a study by Borken et al. (2002) on three European forests, soil temperature at the 10 cm depth explained 73% to 86% of temporal variation in soil respiration.

The relationship between soil respiration and soil moisture can be expressed as a quadratic. The 20% of soil moisture was the critical point, which is higher than the 19% reported by (Keith 1997). Correlations between the 10-day average carbon emissions and soil moisture were not significant at the $P = 0.05$ levels. Zhang et al. (2011) also obtained a similar conclusion in their study. This may be attributed to the inconsistent changing of the rainfall that affected soil moisture. The wetting and drying conditions influenced the CO_2 emission greatly (Muhr et al. 2008). The substantial change in the soil carbon emissions in July of this study, was an effective example for wetting events following an extended summer drought, which was consistent with the findings of Borken et al. (2002).

The study of Xu et al. (2001) indicated that the increase of soil CO_2 efflux was in response to the increase in total nitrogen, phosphorus, organic matter, and fine root biomass.

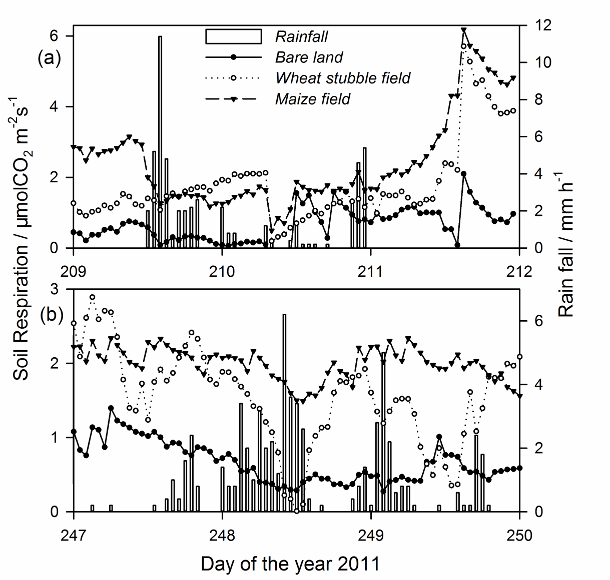

Fig. 6: Response of soil respiration rate to rainfall on July 28 (a) and September 5 (b).

In this study, soil respiration rates in the wheat stubble and maize fields were higher than that in the bare land, which may be largely attributed to the different roots and microbial biomasses. The effect of each of these factors may not be individually explained, because these factors are often strongly inter-correlated and co-vary with the soil organic matter content and root respiration, which are major sources of soil respiration.

CONCLUSIONS

Soil respiration rates in the bare land, wheat stubble field, and maize field indicated a typical temporal dynamic, which was considerably different. Interactions among temperature, water content, rainfall, and others had a combined influence on soil respiration. A more comprehensive study may be needed to understand accurately the relationship between soil respiration and these interactions.

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