

# How do environmental factors and different fertilizer strategies affect soil CO<sub>2</sub> emission and carbon sequestration in the upland soils of southern China?

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## ARTICLE INFO

### Article history:

Received 10 August 2012

Received in revised form 23 May 2013

Accepted 26 May 2013

### Keywords:

Soil CO<sub>2</sub> flux

Winter wheat

Maize

Carbon sink

Carbon source

Carbon balance

## ABSTRACT

Upland soils have been identified as a major CO<sub>2</sub> source induced by human activities, such as fertilizer applications. The aim of this study is to identify the characteristics of soil CO<sub>2</sub> emission and carbon balance in cropland ecosystems after continuous fertilizer applications over decades. The measurements of soil surface CO<sub>2</sub> fluxes throughout the years of 2009 and 2010 were carried out based on a fertilization experiment (from 1990) in a double cropping system rotated with winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) in upland soil in southern China. Four treatments were chosen from the experiment for this study: no-fertilizer application (SR), nitrogen–phosphorus–potassium chemical fertilizers (NPK), NPK plus pig manure (NPKM) and pig manure alone (M). Results showed that the mean value of soil CO<sub>2</sub> fluxes from 08:00 to 10:00 am could represent its daily mean value in summer period (June–August) and that from 09:00 am to 12:00 pm for the rest season of a year. Soil temperature and moisture combined together could explain 70–83% of variations of CO<sub>2</sub> emission. Annual cumulative soil CO<sub>2</sub> fluxes in the treatments with manure applications ( $8.2 \pm 0.8$  and  $11.0 \pm 1.2 \text{ t C ha}^{-1}$  in 2009, and  $7.9 \pm 0.9$  and  $11.1 \pm 1.2 \text{ t C ha}^{-1}$  in 2010 in NPKM and M, respectively) were significantly higher than those in the treatments with non-manure addition ( $2.5 \pm 0.2$  and  $3.4 \pm 0.2 \text{ t C ha}^{-1}$  in 2009, and  $2.1 \pm 0.2$  and  $3.7 \pm 0.3 \text{ t C ha}^{-1}$  in 2010 in SR and NPK, respectively). However, the treatments with manure applications represented a carbon sink in the soil (carbon output/input ratio < 1.0), which demonstrated potential for carbon sequestration.

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## 1. Introduction

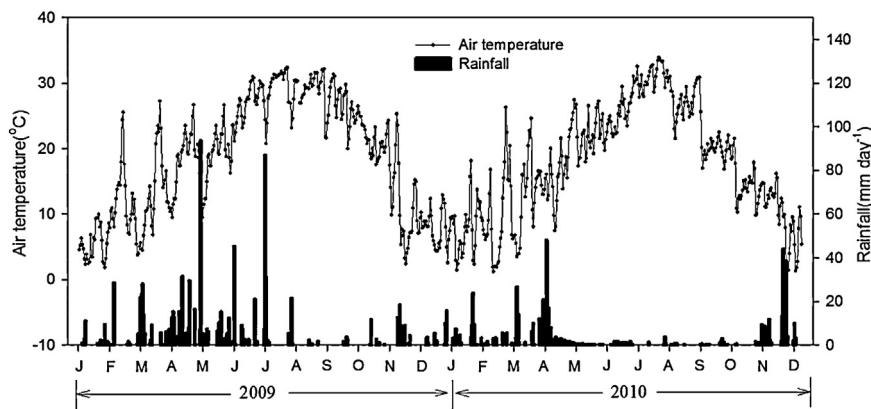
Annual global soil CO<sub>2</sub> emissions contribute to about 25% of the total carbon (C) exchange between the atmosphere and terrestrial ecosystems (Schlesinger and Andrews, 2000). Therefore, an important approach to reduce CO<sub>2</sub> emissions into the atmosphere is to sequester C in soils (Mancinelli et al., 2010). Soil C emission into the atmosphere is thought to be controlled by factors such as, soil temperature and moisture, quantity and quality of substrate, vegetation type, microbial biomass and its activity, and field management (Curtin et al., 2000; Ding et al., 2007; Li et al., 2008). So, it is essential we fully understand the influence of these factors on soil CO<sub>2</sub> emission.

C storage in agro-ecosystems is very sensitive to management practices. Fertilization, especially manure application, has been identified as an essential practice apart from the functions for soil fertility and agricultural production because the amount of residue returned to soils can be increased (Zhang et al., 2009). The dynamics of C balance in a cropland ecosystem is determined by the soil heterotrophic respiration and net primary production of vegetation. An accurate calculation of the C balance of cropland systems is necessary to determine if the system is a sink or source of C under various field managements, especially manure applications (Li et al., 2010; Mancinelli et al., 2010). Whilst it is relatively straight forward to monitor the removal of economic products and residues from a cropland ecosystem, it is more difficult to estimate other components of C balance in the system, e.g. C fluxes from soils via CO<sub>2</sub> and residential time of organic matter added into soils through residual retention of crops and manure applications.

Upland red soil, developed from Quaternary red clay and classified as Ferralic Cambisol (FAO, 1988), covers 1.13 million km<sup>2</sup>,

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**Fig. 1.** Daily air temperature and rainfall at Qiyang long-term experimental site during 2009 and 2010.

accounting for 11% of the total land in China (Lu and Shi, 2000). It is a dominant soil type in southern China with subtropical monsoon climate. Under such a climate with high rainfall and temperature, the region may emit vast amounts of greenhouse gases (Yang et al., 2007). But very few reports on the measurement of soil CO<sub>2</sub> emission have been made. In addition, continuous fertilization experiments on cropland over decades in the region are extremely rare so that it restricts our capability to assess the impact of long-term continuous fertilization on soil CO<sub>2</sub> emission and C balance. Thus, the aims of this study, based on a 19-years long-term field experiment, are to (i) investigate how main environmental factors control diurnal and seasonal variations of soil CO<sub>2</sub> emission; (ii) identify the effect of long-term organic and inorganic fertilizer applications on soil CO<sub>2</sub> emissions; and (iii) estimate C sequestration potential under different fertilizer managements.

## 2. Materials and methods

### 2.1. Study site

This study was based on a long-term field experiment that has been conducted since September 1990 at the experimental station of the Chinese Academy of Agricultural Sciences, located at Qiyang (26°45' N, 111°52' E), Hunan Province of southern China where red soil is a dominant soil type. Annual temperature is 18 °C and annual rainfall is about 1431 mm yr<sup>-1</sup>. Averaged annual evaporation is 1374 mm with a peak in July (<http://cdc.cma.gov.cn>). The dynamics of daily air temperature and precipitation are shown in Fig. 1. The average annual temperature in 2009 and 2010 were 18.3 and 17.8 °C, respectively. The highest temperature was found in August, and the lowest in February. Precipitation in 2009 and 2010 was 948 and 594 mm yr<sup>-1</sup>, respectively. About 70% of annual precipitation fell between April and August (30% of precipitation fell in June–August) in 2009 and about 70% of annual precipitation fell between April and November in 2010. Annual accumulated temperature when the daily temperature is greater than 10 °C is ca. 5600 degree-days.

The initial soil samples were taken in the start of the long-term experiment (1990), the top soil (~20 cm) had a soil organic carbon (SOC) of 8.5 g kg<sup>-1</sup>, total nitrogen (TN) of 1.1 g kg<sup>-1</sup>, total phosphorus (TP) of 0.5 g kg<sup>-1</sup>, total potassium (TK) of 13.3 g kg<sup>-1</sup>, available nitrogen (N<sub>av</sub>) of 79 mg kg<sup>-1</sup>, available P (P<sub>av</sub>) of 11 mg kg<sup>-1</sup>, available K (K<sub>av</sub>) of 122 mg kg<sup>-1</sup>. Their changes during the experiment at the site are shown in Table 1. The soil in this region is quite acidic, having a pH of 5.7 (1:1, w/v, water) and low organic matter content due to intense weathering of soil minerals, rapid decomposition of soil organic matter under the warm and moist climate and less input of organic matter into the soil when the long-term

experiment started. As a result, the soil had a lower C–N ratio in the top soil.

### 2.2. Experimental design

The cropping system is a rotation of winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) from the start of the experiment. Four fertilization treatments from the experiment were used in this study: non-fertilizer application (SR thereafter), inorganic nitrogen (N), phosphorus (P) and potassium (K) combination (NPK thereafter), inorganic NPK fertilizers and pig manure combination (NPKM thereafter) and pig manure alone (M thereafter). There were two replicates per treatment. Each treatment plot had an area of 196 m<sup>2</sup> and was isolated by 100-cm width cement baffle plates along the boundaries.

N, P and K fertilizers were urea, calcium superphosphate, and potassium chloride, respectively. The N content in pig manure was 16.7 ± 1.1 and 17.6 ± 0.9 g kg<sup>-1</sup> in 2009 and 2010, respectively, using the method described by Black (1965). The C content from oven-dried manure was 382 ± 26 and 369 ± 31 g kg<sup>-1</sup> in 2009 and 2010, respectively, using the method of vitriol acid-potassium dichromate oxidation (Walkley and Black, 1934). The C/N ratio of manure was 23 and 21 in 2009 and 2010, respectively. Quantities of fertilizer application for each treatment during the growing seasons are shown in Table 2. All the treatments except SR received the same amount of N (300 kg ha<sup>-1</sup>) but other nutrient elements varied. In the fertilizer treatments, fertilizer and manure were applied as basal dressing for summer maize while 30% of it as basal dressing and rest as top dressing for winter wheat in mid-November.

For each experimental year, winter wheat (*T. aestivum* L.) 'Xiangmai 4' was sown in early November in previous year and harvested in early May, while summer maize (*Zea mays* L.) hybrid 'Yedan 13' was intercropped in early April, and harvested in July. Then a fallow season was followed until the next growing season of winter wheat. There are four rows of winter wheat within a strip (100 cm) and two rows of maize were between the wheat trips with a row distance of 50 cm. Crops were harvested manually by cutting straws close to the ground. Thus, stubble left in the field could be negligible. All above-ground biomass are removed from the fields. Herbicides and pesticides were applied during the growth periods whenever needed.

### 2.3. Soil sample analysis

Soil samples were collected from the topsoil (0–20 cm) after maize harvested each year. 5–10 cores with 5 cm in diameter were randomly sampled for each plot. Soils from the cores were mixed thoroughly and then four replicates (2 kg soil for each replicate)

Treatment	Soil properties in the topsoil (0–20 cm) at Qiyang experimental site in 1990 and 2009.						Exchangeable Ca <sup>2+</sup> (cmol kg <sup>-1</sup> )				
	Bulk density (g cm <sup>-3</sup> )	pH (1:1, w/v, water)	SOC (g kg <sup>-1</sup> )	C stock (Mg ha <sup>-1</sup> )	Total (g kg <sup>-1</sup> )	N	P	K	N	Olsen-P	K
1990	1.19 ± 0.05b	5.7 ± 0.2ab	8.5 ± 0.4d	20.4 ± 1.0c	1.1 ± 0.05b	0.5 ± 0.02c	13.3 ± 0.5ab	79 ± 7.1b	11 ± 1.0c	122 ± 25c	5.00 ± 0.25c
2009	1.31 ± 0.09a	5.9 ± 0.2ab	7.4 ± 0.4d	19.3 ± 1.0c	0.9 ± 0.03b	0.5 ± 0.03c	15.6 ± 0.6a	68 ± 6.0bc	3 ± 0.4c	60 ± 2.1d	5.00 ± 0.02c
SR	1.20 ± 0.10b	4.5 ± 0.1b	10.0 ± 0.5c	23.7 ± 1.2c	1.2 ± 0.10ab	1.1 ± 0.09b	14.1 ± 2.0a	92 ± 15.9b	36 ± 13.0b	181 ± 47.8b	0.57 ± 0.05d
NPK	1.26 ± 0.12ab	6.3 ± 0.2a	14.1 ± 1.1b	35.6 ± 2.8ab	1.5 ± 0.23a	1.7 ± 0.26a	14.7 ± 2.1a	117 ± 16.8ab	209 ± 46.7a	278 ± 14.9a	8.25 ± 0.21b
NPKM	1.34 ± 0.03a	6.8 ± 0.2a	15.3 ± 0.5a	41.1 ± 1.3a	1.5 ± 0.17a	1.8 ± 0.25a	14.9 ± 0.5a	140 ± 19.0a	184 ± 63a	330 ± 56.9a	10.77 ± 0.17a
M											

Numbers with the same letter are not significantly ( $P < 0.05$ ) different among four treatments in each column.

from the soils were taken. Sample soils were air-dried and then sieved through 2 mm screen before analyzing for pH (1:1, w/v, water). Sub-samples of the sieved soils were milled to 0.25 mm for the measurement of SOC and total N content with the same methods as those for pig manure described in the previous section. Soil available nitrogen content (Nav) was measured following the procedures described by Lu (2000).

#### 2.4. CO<sub>2</sub> emission measurement

Soil CO<sub>2</sub> flux from soil surface measured by soil respiration ( $R_s$ , thereafter), and soil temperature and moisture at –5 cm were measured from January 1, 2009 by an Automatic CO<sub>2</sub> Exchange System (ADC BioScientific Limited, UK). The system is equipped with a static soil chamber (23 cm in diameter and 10 cm height), an infra-red gas analyzer, a sensor for detecting photosynthetic active radiation, a moisture sensor (SM200, Delta-T Devices Ltd., UK) and two soil temperature sensors. In each plot three collars were randomly installed immediately after ploughing each year to avoid disturbing the soils with the chamber when measurements were made. One collar from a plot was chosen randomly during one measurement event. Each measurement lasted 5 min with the interval of 15 min between measurements. In order to make measurement on a treatment on the same dates each month, the measurements were continuously taken on each treatment with three replications for three days (72 h) in turn and the sequence was: SR, NPK, NPBM then M. The soil CO<sub>2</sub> fluxes were calculated at half-month period to reduce the error.

#### 2.5. Plant measurement

Wheat and corn straw was removed from the fields and only root, stubble (6–10 cm above-ground) residues and weeds were retained after the grain harvest. Wheat spikes (or corn cobs) and straw were air-dried for 72 h. The spikes or cobs were threshed for grains. The grains and straw were oven-dried at 70 °C to a stable moisture level, and then weighted separately.

#### 2.6. Carbon balance and stock of cropping system

C contents in wheat, maize and weeds were measured by acid-potassium dichromate oxidation (Walkley and Black, 1934). They were 445, 458 and 398 g kg<sup>-1</sup> for wheat, maize and weeds, respectively, C input from the roots of maize and wheat was assumed as 30% of C in aboveground dry matter (Bhattacharyya et al., 2007; Chander et al., 1997; Kuzyakov and Domanski, 2000). Organic material from root systems was considered as C input into the topsoil for all the treatments. For the NPBM and M treatments, C input includes the contribution of manure as well. Weeds were return to the soil as C input.

Root respiration was excluded from C output. It was treated as a part of crop C cycling. Root respiration was estimated as 18% of C in total maize and wheat biomass (Cai et al., 2006; Rochette and Flanagan, 1997). C output was calculated as total soil CO<sub>2</sub> flux after a subtraction of root respiration. An emission coefficient  $C_i$ , C output ( $C_{output}$ ) per unit C input ( $C_{input}$ ) into a system, can be used to assess the status of C balance in the system.  $C_i > 1.0$  indicates a depletion of SOC from the system (soil as a CO<sub>2</sub> source); while  $C_i < 1.0$  means SOC accumulation in soil (soil as a CO<sub>2</sub> sink).

SOC stock ( $P_{SOC}$ , Mg ha<sup>-1</sup>) in the soil profile was calculated according to Zinn et al. (2005):

$$P_{SOC} = \sum_{i=1}^n V_i \cdot BD_i \cdot c_{SOC,i} \quad (1)$$

**Table 1**

Soil properties in the topsoil (0–20 cm) at Qiyang experimental site in 1990 and 2009.

**Table 2**

Amount of N, P and K fertilizers in different cropping season and pig manure applied for the fertilization treatments in each year since 1990 ( $\text{kg ha}^{-1}$ ).

Treatment	Fertilizer N		Fertilizer P		Fertilizer K		C input from pig manure		
	Wheat	Maize	Wheat	Maize	Wheat	Maize	2009	2010	Annual C input (since 1990)
NPK	90	210	16	37	31	73	0	0	0
NPKM <sup>a</sup>	27	63	16	37	31	73	4851 ± 479	4452 ± 435	4500–5000
M <sup>a</sup>	0	0	0	0	0	0	6931 ± 523	6361 ± 539	6500–7000

<sup>a</sup> N deficit was compensated by N in manure.

where  $i$  is the  $i$ th soil layer,  $n$  is the number of soil layer in the soil profile,  $V_i$  is the soil volume ( $\text{m}^3 \text{ha}^{-1}$ ) of the  $i$ th layer,  $BD_i$  is the soil bulk density ( $\text{Mg m}^{-3}$ ) of the  $i$ th layer and  $c_{SOC,i}$  is the SOC concentration ( $\text{Mg C Mg}^{-1} \text{soil}$ ) of the  $i$ th layer. In our study, we considered only the surface layer (0–20 cm).

### 2.7. Quantitative effects of soil temperature and moisture on $R_s$ and statistical analysis

In order to assess the combined effect of  $T_s$  (soil temperature at –5 cm) and  $W_s$  (soil moisture at –5 cm) on  $R_s$ , bivariate models were employed to examine the relationship (Li et al., 2011):

$$R_s = \alpha + \beta T_s + \beta_1 W_s \quad (2)$$

$$R_s = \alpha e^{\beta T_s} W_s^{\beta_1} \quad (3)$$

$$R_s = \alpha T_s^\beta W_s^{\beta_1} \quad (4)$$

$$R_s = \alpha e^{\beta T_s + \beta_1 W_s} \quad (5)$$

where  $\alpha$ ,  $\beta$  and  $\beta_1$  are fitted parameters.

Regressions of daily fluxes against the data measured on the hour on the same day were made. The analysis was used to find out the best time in a day on which the sampled data would represent the daily mean  $\text{CO}_2$  flux.

Normal and variance tests were used to assess if the bivariate models passed or failed the statistical analysis. The ANOVA method was applied to compare mean soil  $\text{CO}_2$  fluxes between 09:00 am and 12:00 pm, mean daily fluxes, C contents in above-ground (i.e. grain and straw) and root, manure C input,  $C_{input}$  and  $C_{output}$  among various fertilization treatments at  $P=0.05$ . A two-way ANOVA was applied to analyze the effects of fertilization and season on soil  $\text{CO}_2$  fluxes. Post hoc test (TukeyHSD) was used to further investigate the main or interactive effect of fertilization and season on the fluxes. All statistical analysis was performed with SPSS v. 17.0 for Windows (SPSS, Inc., 1999, Chicago, USA, [www.spss.com](http://www.spss.com)).

## 3. Results

### 3.1. Diurnal variation of soil $\text{CO}_2$ flux

Monitoring data showed that soil  $\text{CO}_2$  flux had an obvious diurnal variation, although the daily amplitude varied. The lowest flux appeared between 03:00 and 06:00 am and the highest between 14:00 and 16:00 pm, occasionally between the noon and 13:00 pm. The diurnal variation of soil  $\text{CO}_2$  flux is in agreement with  $T_s$  variation (Fig. 2).

Comparing the mean values of soil  $\text{CO}_2$  flux between 09:00 am and 12:00 pm with mean daily fluxes over the two experimental years, it was found that the mean values between 09:00 am and 12:00 pm in a whole year except summer (June–August) were not significantly different from correspondent daily values (Table 3). In summer, linear regression analysis between the main daily  $\text{CO}_2$  flux and the  $\text{CO}_2$  fluxes in an hour in the same day showed that the slopes of the regressions at 08:00 and 10:00 am were the closest

to the unity (Table 4). The soil  $\text{CO}_2$  flux at 08:00 am was 4% lower than the daily mean flux (not significant) and that at 10:00 am was 1% higher (not significant). Thus, soil  $\text{CO}_2$  fluxes from 08:00 am to 10:00 am could represent correspondent daily values during the summer period.

### 3.2. Seasonal variation of soil $\text{CO}_2$ flux

Soil  $\text{CO}_2$  fluxes also showed an obvious seasonal variation during the experimental monitoring period, following a similar trend to soil temperature at –5 cm depth (Fig. 3). The dynamics of soil  $\text{CO}_2$  emission rates from all the treatments followed the same pattern with time in both experimental years. The lowest monthly flux for the treatments was in January and the highest in July in 2009. Among the treatments, the M treatment had the highest monthly flux in the year. However, the lowest monthly  $\text{CO}_2$  flux occurred in different months for different treatments in 2010. The minimum monthly  $\text{CO}_2$  flux for the SR and NPK treatments appeared in February ( $4.1 \pm 0.6$  and  $10.9 \pm 1.2 \text{ mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$ , respectively) while that for the NPKM and M treatments happened in January ( $72.4 \pm 9.7$  and  $60.2 \pm 8.8 \text{ mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$ , respectively).

### 3.3. Crop carbon in biomass and carbon balance

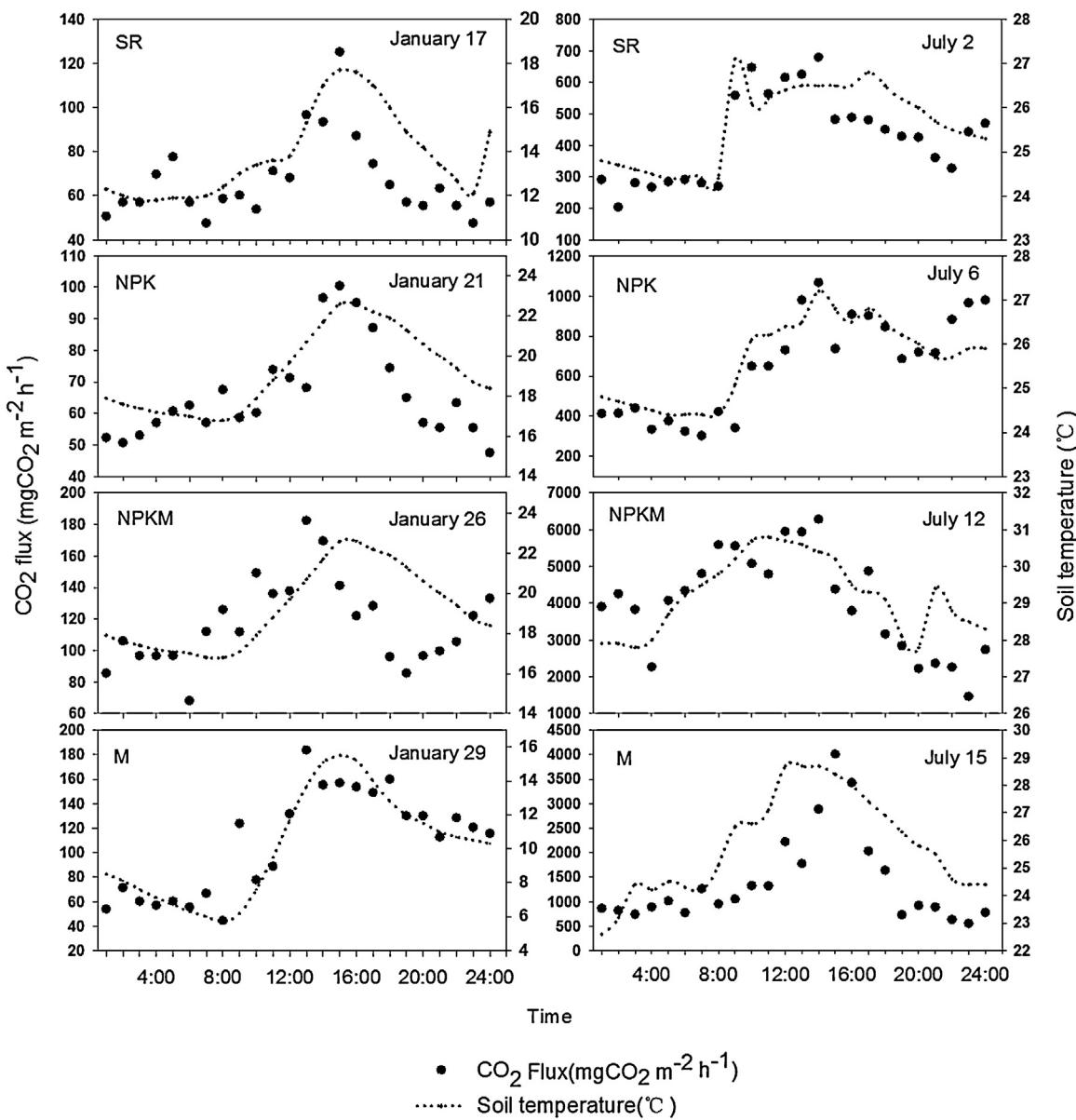
Crop C and the components of the annual C balance are shown in Table 5. Above- and below-ground biomass of the crops was significantly higher in the NPKM and M treatments than that in the SR and NPK treatments. The highest annual crop biomass was observed in the NPKM treatment in 2009 and 2010. In addition, weed biomass accumulation in four treatments in both 2009 and 2010 following the order statistically: M=NPKM=NPK>SR (Table 5).

Annual cumulated  $\text{CO}_2$  fluxes differed between four treatments in two years. However, the magnitude of the cumulated fluxes followed the same order each year: M>NPKM>NPK>SR. Annual C input in the treatments ranged from  $1.7 \pm 0.2$  to  $11.3 \pm 1.0 \text{ t C ha}^{-1}$  in 2009 and from  $1.7 \pm 0.2$  to  $10.4 \pm 0.9 \text{ t C ha}^{-1}$  in 2010, respectively. Annual C output ranged from  $2.3 \pm 0.2$  to  $9.2 \pm 0.8 \text{ t C ha}^{-1}$  in 2009, and from  $1.8 \pm 0.1$  to  $9.7 \pm 0.9 \text{ t C ha}^{-1}$  in 2010, respectively (Table 5). The C balance from the NPK, NPKM and M treatments indicated that soil was a C sink ( $C_i < 1.0$ ).

## 4. Discussion

### 4.1. Changes of soil temperature and moisture vs. dynamics of soil $\text{CO}_2$ emission

The sampled data showed that maximum  $\text{CO}_2$  flux in a day appeared at noon and the minimum appeared in early morning, which supports the finding by (Li et al., 2011). Earlier studies showed that the mean value of soil  $\text{CO}_2$  fluxes between 9:00 am and 12:00 pm could represent its daily mean (Davidson et al., 1998; Xu and Qi, 2001; Yan et al., 2009). However, our data showed that this was not verified during the summer period (June–August). The

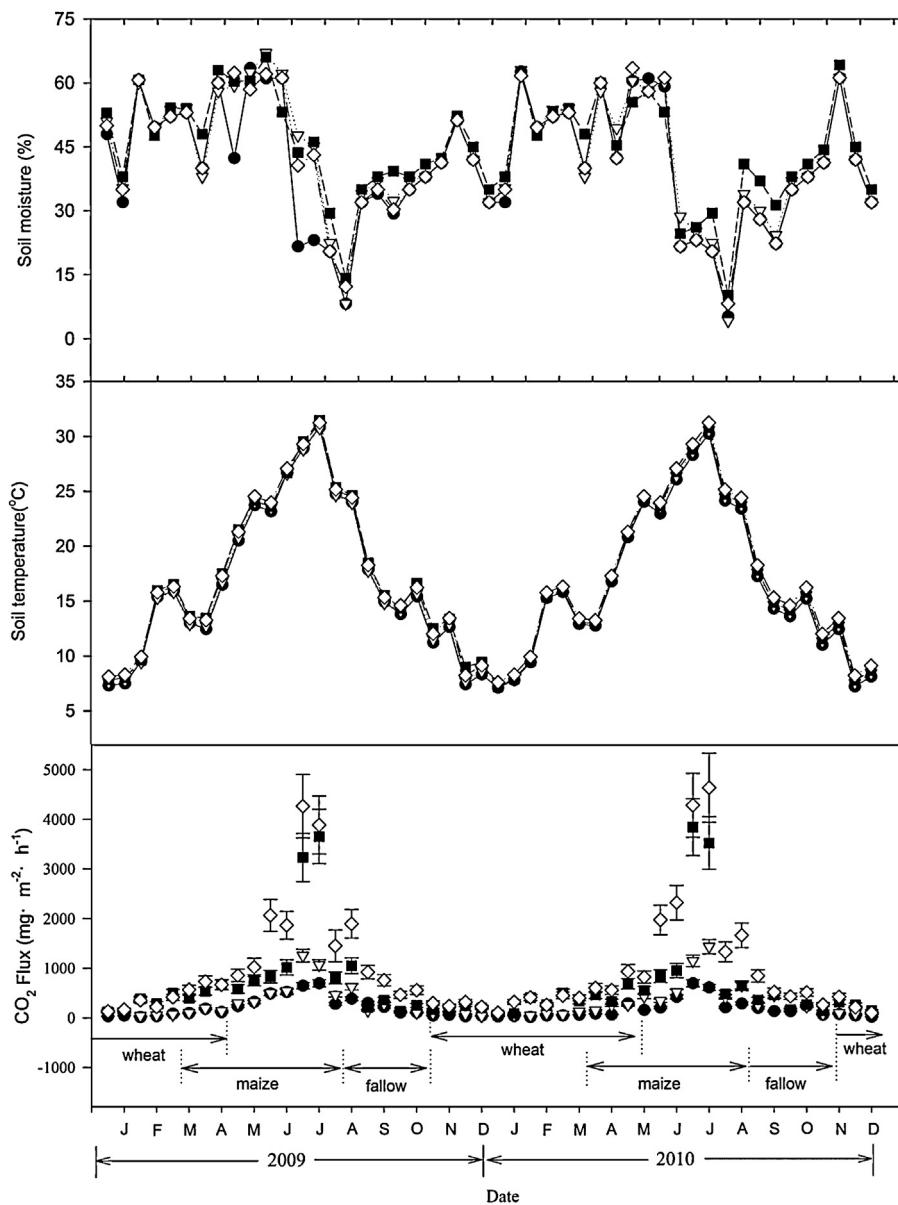


**Fig. 2.** Diurnal variation of CO<sub>2</sub> fluxes from different treatments during the wheat growing season (left panel) and maize growing season (right panel). Solid circles in the figure are hourly CO<sub>2</sub> flux (mgCO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>) and dotted lines for soil temperature at 5 cm depth (°C).

regression analysis between the daily mean CO<sub>2</sub> fluxes and the sampled data on the hours suggested that soil CO<sub>2</sub> fluxes between 08:00 am and 10:00 am in a day could represent correspondent daily value better in summer. In order to estimate soil CO<sub>2</sub> fluxes around the year from agricultural systems accurately, we proposed that 09:00 am to 12:00 pm in spring, autumn and winter, and 08:00 am to 10:00 am in summer would be suitable times for gas samplings.

There are number of environmental and biological factors to control soil CO<sub>2</sub> fluxes. Of which, soil temperature and moisture are two dominant environmental factors (Andrén et al., 2007). For example, soil temperature could account for about 70% of the diurnal variation in soil CO<sub>2</sub> flux (Drewitt et al., 2002; Gaumont-Guay et al., 2006; Tang et al., 2005). Moreover, the relationship between W<sub>s</sub> and the flux has been widely reported in various experiments (Davidson et al., 1998; Kowalenko et al., 1978; Lipiec et al., 2003; Xu and Qi, 2001; Yuste et al., 2003). For instance, Ding et al. (2007) reported that this correlation was significant when W<sub>s</sub> was <70%, and then declined sharply when W<sub>s</sub> > 70%.

Empirical correlations between soil CO<sub>2</sub> flux and T<sub>s</sub> or W<sub>s</sub> may confound each other. Clearly, soil CO<sub>2</sub> flux is the result of interactive effects of T<sub>s</sub> and W<sub>s</sub>. It was reported that the soil CO<sub>2</sub> flux significantly depended on T<sub>s</sub> when soil water content was in an appropriate range, and was controlled by W<sub>s</sub> when soil temperature is at 10 °C (Li et al., 2008). Thus, four different models (Eqs. (2)–(5)) were employed to quantitatively analyze the combined impact of T<sub>s</sub> and W<sub>s</sub> on CO<sub>2</sub> flux for each treatment. It is noted that each of the four equations could be used to describe the relations of CO<sub>2</sub> flux to both T<sub>s</sub> and W<sub>s</sub> together and could explain 34–83% of variations of the emission (Table 6). Li et al. (2008) found that two-variable equations were much better than one-variable equations in predicting the CO<sub>2</sub> flux for whole seasonal measurements. The other similar results also supported this conclusion (Xu and Qi, 2001; Yuste et al., 2003). Hence, two-variable models were better to estimate the regional or global CO<sub>2</sub> budget under different climate conditions or extreme climates (e.g. drought, frozen period). Nevertheless, among the four models, the best form is Eq. (3) (i.e. R<sub>s</sub> = αe<sup>βT<sub>s</sub></sup>W<sub>s</sub><sup>β1</sup>) that passed both the normal and variance tests.



**Fig. 3.** Seasonal variations in soil moisture (a), soil temperature (b) and soil CO<sub>2</sub> emission (c) in the fields of SR (●), NPK (▽), NPKM (■) and M (◊) treatments from January 2009. The symbols in the figure indicate the half-monthly mean of measured values in the month.

#### 4.2. Impact of different fertilizations on soil CO<sub>2</sub> emissions

There is controversy concerning the effect of N fertilization on soil CO<sub>2</sub> emission: either stimulation (Liljeroth et al., 1994; Gallardo and Schlesinger, 1994) or inhibition (Cardon et al., 2001; Giardina et al., 2004). Ding et al. (2010) argued that stimulatory or inhibitory effect of N fertilization on soil CO<sub>2</sub> flux might depend on the concentration of decomposable fraction of SOC. Our results supported the conclusion that soil CO<sub>2</sub> flux in N application treatment was significantly higher than that in SR treatment in this region.

Previous studies showed that soil CO<sub>2</sub> fluxes in the manure treatments were significantly higher than those in the non-manure treatments (Ding et al., 2007; Mancinelli et al., 2010). The conclusion was supported by our results. After 19 years of continuous manure application, the SOC contents in the NPKM and M treatments in 2009 were enhanced by 64 and 78% compared with the initial value, respectively, whereas only 15% increase in the NPK treatment and decrease in the SR treatment. The regression analysis (Fig. 4) showed that soil CO<sub>2</sub> flux was highly related to SOC

content, which strongly suggested that a higher CO<sub>2</sub> flux do not always reduce SOC and C be still sequestered in the soils through increasing more plant production and/or adding manure. The result was also supported by the published observations that soil CO<sub>2</sub> flux was highly correlated to amount of C input into soils (Ding et al., 2007; La Scala et al., 2000).

Soil CO<sub>2</sub> fluxes were also significantly correlated with Navs (Fig. 5). Navs in the NPKM and M treatments were significantly higher than that in the non-manure treatments (NPK and SR) in spite of the same N input level in the fertilized treatments. Higher Navs in the manure-added treatments led to more crop dry matter accumulation including roots, and microbial activities vigorous, which would have more C respired and more root residues decomposed (Schüßler et al., 2000; Yi et al., 2007). In addition, increasing Olsen-P and available K contents by regularly applying manure with suitable C/N ratios would provide favorable conditions for improving soil fertility (Marinari et al., 2006). In addition, exchangeable Ca<sup>2+</sup> contents in manure treatment were higher than those in NPK and SR treatment. It was noted that soil exchangeable Ca<sup>2+</sup> content

**Table 3**

Mean soil CO<sub>2</sub> fluxes between 09:00 am and 12:00 pm and mean daily fluxes (mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>) over two years from different treatments.

Treatment		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SR	9–12 <sup>A</sup>	50 ± 13 <sup>c</sup>	33 ± 8 <sup>c</sup>	100 ± 12 <sup>b</sup>	125 ± 31 <sup>c</sup>	325 ± 22 <sup>c</sup>	469 ± 43 <sup>d</sup>	809 ± 105 <sup>d</sup>	475 ± 53 <sup>d</sup>	226 ± 33 <sup>c</sup>	105 ± 22 <sup>c</sup>	60 ± 17 <sup>c</sup>	41 ± 9 <sup>c</sup>
	Daily <sup>B</sup>	46 ± 9 <sup>c</sup>	35 ± 11 <sup>c</sup>	96 ± 7 <sup>b</sup>	115 ± 22 <sup>c</sup>	322 ± 39 <sup>c</sup>	521 ± 66 <sup>d</sup>	697 ± 89 <sup>de</sup>	386 ± 87 <sup>d</sup>	221 ± 42 <sup>c</sup>	110 ± 19 <sup>c</sup>	62 ± 23 <sup>c</sup>	44 ± 11 <sup>c</sup>
NPK	9–12	117 ± 32 <sup>ab</sup>	47 ± 16 <sup>c</sup>	107 ± 18 <sup>b</sup>	138 ± 19 <sup>c</sup>	319 ± 41 <sup>c</sup>	483 ± 52 <sup>d</sup>	1206 ± 131 <sup>d</sup>	728 ± 88 <sup>b</sup>	301 ± 61 <sup>b</sup>	99 ± 25 <sup>c</sup>	125 ± 42 <sup>b</sup>	39 ± 12 <sup>c</sup>
	Daily	122 ± 29 <sup>a</sup>	52 ± 9 <sup>c</sup>	103 ± 21 <sup>b</sup>	141 ± 28 <sup>c</sup>	323 ± 55 <sup>c</sup>	543 ± 55 <sup>d</sup>	1067 ± 109 <sup>d</sup>	623 ± 75 <sup>bc</sup>	289 ± 57 <sup>b</sup>	104 ± 20 <sup>c</sup>	121 ± 29 <sup>b</sup>	36 ± 7 <sup>c</sup>
NPKM	9–12	120 ± 38 <sup>a</sup>	284 ± 44 <sup>ab</sup>	398 ± 43 <sup>a</sup>	520 ± 77 <sup>b</sup>	629 ± 63 <sup>b</sup>	964 ± 106 <sup>c</sup>	4169 ± 427 <sup>ab</sup>	1200 ± 116 <sup>a</sup>	338 ± 42 <sup>b</sup>	232 ± 31 <sup>b</sup>	127 ± 32 <sup>b</sup>	211 ± 51 <sup>b</sup>
	Daily	117 ± 19 <sup>ab</sup>	282 ± 53 <sup>ab</sup>	394 ± 71 <sup>a</sup>	537 ± 93 <sup>b</sup>	583 ± 71 <sup>b</sup>	831 ± 75 <sup>c</sup>	3231 ± 266 <sup>c</sup>	1053 ± 95 <sup>b</sup>	356 ± 66 <sup>b</sup>	252 ± 35 <sup>b</sup>	122 ± 36 <sup>b</sup>	199 ± 32 <sup>b</sup>
M	9–12	135 ± 33 <sup>a</sup>	356 ± 61 <sup>a</sup>	401 ± 66 <sup>a</sup>	718 ± 64 <sup>a</sup>	822 ± 98 <sup>a</sup>	1862 ± 134 <sup>a</sup>	5158 ± 432 <sup>a</sup>	1000 ± 105 <sup>a</sup>	932 ± 98 <sup>a</sup>	461 ± 39 <sup>a</sup>	287 ± 42 <sup>a</sup>	345 ± 59 <sup>a</sup>
	Daily	132 ± 25 <sup>a</sup>	349 ± 68 <sup>a</sup>	413 ± 89 <sup>a</sup>	733 ± 89 <sup>a</sup>	856 ± 72 <sup>a</sup>	1564 ± 119 <sup>b</sup>	4263 ± 301 <sup>ab</sup>	1064 ± 81 <sup>a</sup>	923 ± 69 <sup>a</sup>	466 ± 53 <sup>a</sup>	296 ± 31 <sup>a</sup>	322 ± 63 <sup>a</sup>

<sup>a</sup> Mean value of fluxes between 9:00 am and 12:00 pm.

<sup>b</sup> Daily mean flux. Numbers with the same letter are not significantly ( $P < 0.05$ ) different between mean fluxes from 9:00 am to 12:00 pm and mean daily fluxes in a month within the column.

**Table 4**  
Regression parameters and the regression coefficients ( $R^2$ ) in the relationship between the mean daily CO<sub>2</sub> flux and the CO<sub>2</sub> fluxes sampled on an hour on the same day ( $n = 570$  for each hour) during the summer period (June–August).

Sampling time (hours of the day)

$\text{CO}_2$  flux

$a$

$b$

$R^2$

Measurement data from four treatments were adjusted to the linear equation  $f_{\text{dm}} = (qf_{\text{time}}) + b$ , where  $f_{\text{dm}}$  is the mean daily CO<sub>2</sub> flux and  $f_{\text{time}}$  is the CO<sub>2</sub> flux for each measurement time of the day.

\* Significant correlation at the 0.05 level (1-tailed).

\*\* Extremely significant correlation at the 0.01 level (2-tailed).

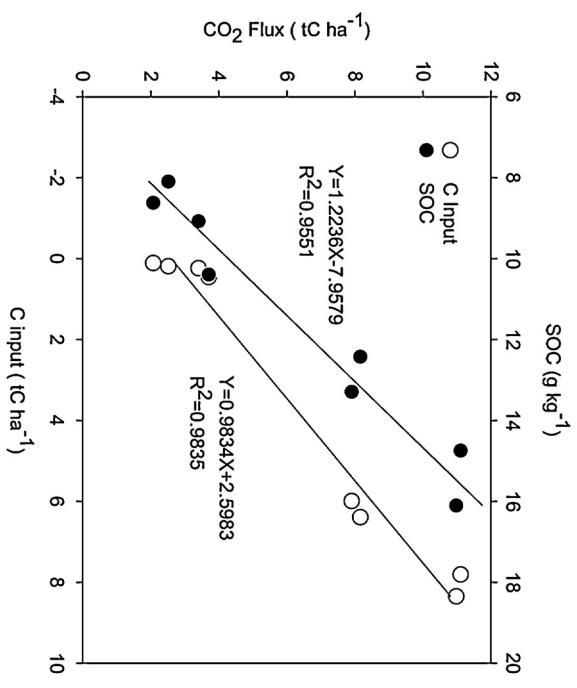


Fig. 4. The relationship between soil CO<sub>2</sub> fluxes and carbon inputs and soil organic carbon (SOC) contents during 2009 and 2010.

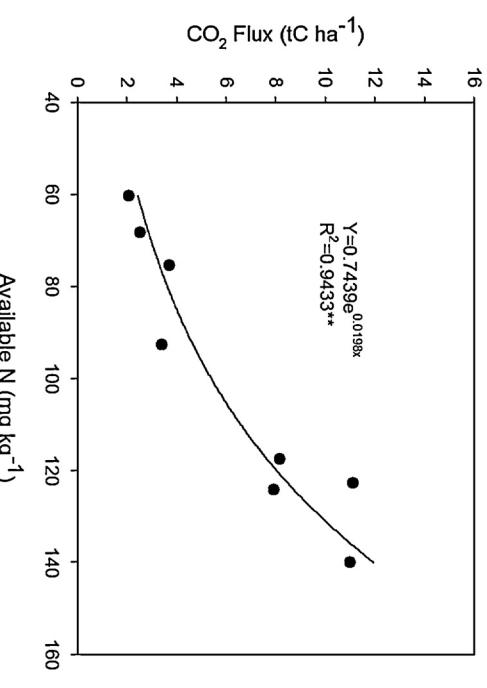


Fig. 5. The relationship between soil CO<sub>2</sub> fluxes and available nitrogen (AN) during 2009 and 2010.

**Table 5**

Soil (0–20 cm) chemical properties, weeds, crop carbon production, carbon input and output from the treatments during the experimental years.

	2009				2010			
	SR	NPK	NPKM	M	SR	NPK	NPKM	M
SOC ( $\text{g kg}^{-1}$ )	7.4 ± 0.4 <sup>c</sup>	10.0 ± 0.5 <sup>b</sup>	14.1 ± 1.1 <sup>a</sup>	15.3 ± 0.5 <sup>a</sup>	8.6 ± 0.6 <sup>c</sup>	10.4 ± 0.7 <sup>b</sup>	13.3 ± 0.9 <sup>a</sup>	14.7 ± 0.7 <sup>a</sup>
N content ( $\text{g kg}^{-1}$ )	0.9 ± 0.03 <sup>b</sup>	1.2 ± 0.10 <sup>ab</sup>	1.5 ± 0.23 <sup>a</sup>	1.5 ± 0.17 <sup>a</sup>	1.0 ± 0.04 <sup>b</sup>	1.1 ± 0.05 <sup>b</sup>	1.5 ± 0.05 <sup>a</sup>	1.6 ± 0.09 <sup>a</sup>
Soil C/N ratio	8.2	8.3	9.4	10.2	8.6	9.5	8.9	9.2
Wheat root ( $\text{kg Ch}^{-1}$ ) <sup>A</sup>	112 ± 12 <sup>bc</sup>	311 ± 91 <sup>b</sup>	697 ± 67 <sup>a</sup>	588 ± 61 <sup>ab</sup>	187 ± 19 <sup>bc</sup>	297 ± 65 <sup>b</sup>	660 ± 71 <sup>a</sup>	666 ± 70 <sup>a</sup>
Wheat grain and straw ( $\text{kg Ch}^{-1}$ )	374 ± 42 <sup>cd</sup>	1036 ± 305 <sup>b</sup>	2323 ± 225 <sup>a</sup>	1958 ± 205 <sup>a</sup>	623 ± 66 <sup>c</sup>	991 ± 217 <sup>b</sup>	2201 ± 236 <sup>a</sup>	2220 ± 235 <sup>a</sup>
Maize root ( $\text{kg Ch}^{-1}$ ) <sup>A</sup>	110 ± 13 <sup>d</sup>	461 ± 128 <sup>c</sup>	1565 ± 248 <sup>a</sup>	1469 ± 225 <sup>a</sup>	97 ± 27 <sup>d</sup>	455 ± 108 <sup>c</sup>	1345 ± 164 <sup>a</sup>	915 ± 198 <sup>b</sup>
Maize grain and straw ( $\text{kg Ch}^{-1}$ )	365 ± 44 <sup>d</sup>	1536 ± 455 <sup>bc</sup>	5218 ± 825 <sup>a</sup>	4895 ± 752 <sup>a</sup>	324 ± 89 <sup>d</sup>	1517 ± 361 <sup>bc</sup>	4482 ± 547 <sup>a</sup>	3048 ± 662 <sup>b</sup>
Weeds ( $\text{kg Ch}^{-1}$ )	1521 ± 133 <sup>b</sup>	2030 ± 64 <sup>a</sup>	2102 ± 176 <sup>ab</sup>	2350 ± 204 <sup>a</sup>	1459 ± 144 <sup>b</sup>	2122 ± 166 <sup>a</sup>	2200 ± 104 <sup>a</sup>	2411 ± 169 <sup>a</sup>
C fluxes ( $\text{kg Ch}^{-1} \text{y}^{-1}$ )	2510 ± 209 <sup>d</sup>	3402 ± 213 <sup>c</sup>	8163 ± 823 <sup>b</sup>	10,972 ± 1209 <sup>a</sup>	2072 ± 196 <sup>d</sup>	3704 ± 288 <sup>c</sup>	7904 ± 963 <sup>b</sup>	11,101 ± 1231 <sup>a</sup>
$C_{\text{input}}$ ( $\text{kg Ch}^{-1} \text{y}^{-1}$ )	1743 ± 157 <sup>d</sup>	2802 ± 283 <sup>c</sup>	9216 ± 761 <sup>b</sup>	11,338 ± 1013 <sup>a</sup>	1743 ± 190 <sup>d</sup>	2874 ± 339 <sup>c</sup>	8658 ± 774 <sup>b</sup>	10,353 ± 976 <sup>a</sup>
$C_{\text{output}}$ ( $\text{kg Ch}^{-1} \text{y}^{-1}$ ) <sup>B</sup>	2320 ± 221 <sup>c</sup>	2730 ± 351 <sup>c</sup>	6194 ± 667 <sup>b</sup>	9189 ± 861 <sup>a</sup>	1820 ± 132 <sup>cd</sup>	3049 ± 299 <sup>c</sup>	6162 ± 766 <sup>b</sup>	9730 ± 901 <sup>a</sup>
$C_i$	1.33	0.97	0.67	0.81	1.04	1.06	0.71	0.93

<sup>A</sup> It was calculated as 30% of C in aboveground biomass.<sup>B</sup> It was calculated as total soil CO<sub>2</sub> flux after a subtraction of root respiration.Numbers in one row with the same letter are not significantly ( $P < 0.05$ ) between the treatments and years.

was correlated with soil CO<sub>2</sub> emission ( $R^2 = 0.69$ ,  $P < 0.05$ ). A lower soil exchangeable Ca<sup>2+</sup> content in the NPK treatment might due to soil acidity. If the value was excluded, the relationship between the exchangeable Ca<sup>2+</sup> content and soil CO<sub>2</sub> emission was significant ( $R^2 = 0.99$ ,  $P < 0.001$ ). Thus, the soil exchangeable Ca<sup>2+</sup> content was one of the important impact factors on soil CO<sub>2</sub> fluxes as well. As a result of higher C input to the soils in the NPKM and M treatments soil CO<sub>2</sub> fluxes from the treatments were higher than that from the SR and NPK treatments.

#### 4.3. Carbon balance of different fertilizations

Our results indicated that the soils without external fertilizer application (SR) would be a C source ( $C_i > 1.0$ ) and the soils with the manure treatments could be a C sink ( $C_i < 1.0$ ). This supported the conclusions drawn from different soil types in other regions (Li et al., 2010; Mancinelli et al., 2010).

It was reported that increase in soil C stock in a manure treatment might be achieved through more C input through crop residue and manure application (Malhi et al., 2011), or through more SOC locked in the soils by a lower metabolic quotient (microbial respiration per unit biomass) and higher C use efficiency (Marinari et al., 2006). The shift in SOC stocks toward micro-aggregate is beneficial for long-term soil C sequestration (Balesdent et al., 2000). After

19-year continuous fertilization, soil C stocks (0–20 cm) in the NPKM and M treatments increased by 74 and 101% compared to that in the initial year, respectively, while little changes in the SR and NPK treatments (Table 1).

In our study, soil CO<sub>2</sub> emissions had a significant correlation with C/N ratio ( $R^2 = 0.6$ ,  $P < 0.05$ ), which indicated that it is an important factor for the retention of organic carbon in the soil. For the SR treatment, SOC stock showed not significant change (i.e. C input through roots and crop residues merely maintained the level of SOC) but soil total N content declined during the experimental period, which caused the C/N ratio increased from 7.2 to 8.2 (Cong et al., 2012). The significant increasing of SOC and the vacillation of the total N content in the NPKM and M treatments led an increasing of the soil C/N ratios in both 2009 and 2010 (Table 1). On the other hand, the difference in decomposition rate between C and N has been shown to increase the C/N ratio in the manure treatments at this site (Cong et al., 2012). A higher C decomposition rate under the treatments of abundant organic C input from manure with excess N addition at the site might be paid off by the efficiency of microbial assimilation (Marinari et al., 2006). Thus, the drastic increase of C/N ratios in the manure application treatments implied that more C was sequestered into the soils at the continual same N input level although more C was emitted to the atmosphere.

**Table 6**Parameter values of fitted  $R_s$  functions based on soil temperature and moisture at –5 cm and statistical analysis.

Model	Treatment	Coefficients			Statistical test		$R^2$
		A	$\beta$	$\beta_1$	Normal	Variance	
Eq. (2)	SR	-0.076 <sup>*</sup>	0.010 <sup>**</sup>	0.079	F <sup>a</sup>	F	0.407 <sup>**</sup>
	NPK	-0.304 <sup>*</sup>	0.024 <sup>**</sup>	0.134 <sup>*</sup>	p <sup>b</sup>	P	0.689 <sup>**</sup>
	NPKM	-0.605	0.222 <sup>**</sup>	-3.820	P	F	0.659 <sup>**</sup>
	M	-0.697 <sup>*</sup>	0.158 <sup>**</sup>	-1.889	P	F	0.683 <sup>**</sup>
Eq. (3)	SR	0.067 <sup>**</sup>	0.054 <sup>*</sup>	0.247 <sup>*</sup>	P	P	0.702 <sup>**</sup>
	NPK	0.046 <sup>**</sup>	0.082 <sup>**</sup>	0.144 <sup>**</sup>	P	P	0.734 <sup>**</sup>
	NPKM	0.219 <sup>**</sup>	0.371 <sup>**</sup>	0.641 <sup>*</sup>	P	P	0.709 <sup>**</sup>
	M	0.081 <sup>*</sup>	0.141 <sup>**</sup>	0.385 <sup>*</sup>	P	P	0.826 <sup>**</sup>
Eq. (4)	SR	0.004 <sup>**</sup>	1.280 <sup>**</sup>	0.214	P	F	0.611 <sup>**</sup>
	NPK	0.001 <sup>**</sup>	2.028	0.098 <sup>*</sup>	P	P	0.798 <sup>**</sup>
	NPKM	$1.45 \times 10^{-12}$ <sup>**</sup>	8.777 <sup>*</sup>	0.600 <sup>*</sup>	P	P	0.817 <sup>**</sup>
	M	$2.46 \times 10^{-5}$ <sup>**</sup>	3.613 <sup>*</sup>	0.287 <sup>*</sup>	P	P	0.810 <sup>**</sup>
Eq. (5)	SR	0.047 <sup>**</sup>	0.050 <sup>**</sup>	0.444 <sup>*</sup>	P	F	0.342 <sup>*</sup>
	NPK	0.026 <sup>**</sup>	0.089 <sup>**</sup>	0.647 <sup>*</sup>	P	P	0.757 <sup>**</sup>
	NPKM	$4.215 \times 10^{-5}$ <sup>**</sup>	0.379 <sup>**</sup>	2.075	P	P	0.779 <sup>**</sup>
	M	0.046 <sup>**</sup>	0.138 <sup>**</sup>	0.719 <sup>*</sup>	P	P	0.805 <sup>**</sup>

<sup>a</sup> F indicated failure.<sup>b</sup> P indicated pass.

\* Significant correlation at the 0.05 level (1-tailed).

\*\* Extremely significant correlation at the 0.01 level (2-tailed).

Manure application contributes to the increase in SOC in a way that promotes crop dry matter production without altering the decomposition rate of native SOC (Snyder et al., 2009). A large amount of farmyard manure and crop residues applied to the soils increases SOC but could change the decomposition rate of native SOC because the amount of SOC changes toward an equilibrium value (Johnston et al., 2009). Therefore, different forms of external input (manure or chemical fertilizers) to the soils change SOC contents.

In our long-term trial, there was no significant difference in crop production between the NPKM and M treatment while the field in the NPK treatment produced only around half of dry matter in the fields of the NPKM and M treatments. All of three treatments received the same amount of nitrogen, which hinted that N would not be a limited factor for crop production at such an N supply level. There are many environmental factors that influence crop yield directly or indirectly (e.g. manure application inhibited soil acidity). After continuous application of chemical fertilizers, the soil pH value in the NPK treatment declined (Table 1) compared to that in the initial year. The value may cause crop growing in an unfavorable condition. However, crop yield increased significantly in the manure treatments compared to that in the non-manure treatment, which indicated an increasing of plant growth and, in turn, raise root C return to the soils for microbial decomposition.

It should be noted that  $C_i$  calculation in this study excluded the contribution of the production and transportation of chemical fertilizers to CO<sub>2</sub>-equivalent emission. Among the greenhouse gases, C emission from the manufacture and transportation of chemical fertilizers is an important component to calculate C sequestration in a long term experiment (Campbell et al., 2001).

## 5. Conclusion

Soil temperature and moisture combined together could explain 70–83% of the variations of CO<sub>2</sub> emission. Our study proposed that 09:00 am to 12:00 pm in spring, autumn and winter, and 08:00 am to 10:00 am in summer would be suitable periods in a day for gas samplings. After 19 years of continuous fertilization, soil CO<sub>2</sub> flux in the NPK treatment was significantly greater than that in the non-fertilization treatment but SOC stock in the NPK treatment was not significant different from that in the SR treatment. SOC stocks in the manure treatments (NPKM and M), however, were significant higher than those in the NPK and SR treatment. Higher C input, SOC and Nabs in the manure treatments led higher soil CO<sub>2</sub> fluxes compared with that in the NPK treatment in spite of the same amount of N applied during two continuous monitoring years. It was noted that step increases of C stocks and much lower output/input ratio (<1.0) in the manure treatments indicated that the fields with manure amendments represented a C sink in the soils. By contrary, the fields of the NPK and non-fertilization treatments were a C source. Therefore, manure application strategies should be considered in agricultural activities in upland soils of southern China.

## Acknowledgements

The research was financially supported by the National Basic Research Program (2011CB100501) and the National Science Foundation of China (40871148, 40901141, 41001175, and 41171239). The authors acknowledge the colleagues of Key Monitoring Experimental Station of National Agriculture Red Soil Fertility and Fertilizer Efficiency for their unremitting efforts on sampling and data collection. Rothamsted Research is supported by the BBSRC.

## References

- Andrén, O., Kihara, J., Bationo, A., Vanlauwe, B., Kätterer, T., 2007. *Soil climate and decomposer activity in sub-Saharan Africa, estimated from standard weather station data – used in soil carbon balance calculations*. AMBIO 36, 379–386.
- Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil Till. Res.* 53, 215–230.
- Bhattacharyya, R., Kundu, S., Prakash, V., Ghosh, B.N., Gupta, H.S., 2007. Carbon sequestration and relationship between carbon addition and storage under rain-fed soybean-wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil Till. Res.* 92, 87–95.
- Black, C.A., 1965. *Methods of soil analysis, part 2*. Madison, WI, USA.
- Cai, Y., Ding, W.X., Cai, Z., 2006. Soil respiration in a maize-soil ecosystem and contribution of rhizosphere respiration. *Acta Ecol. Sin.* 26, 4273–7280 (in Chinese).
- Campbell, C.A., Zentner, R.P., Selles, F., Liang, B.C., Blomert, B., 2001. Evaluation of a simple model to describe carbon accumulation in a Brown Chernozem under varying fallow frequency. *Can. J. Soil Sci.* 81, 383–394.
- Cardon, Z.G., Hungate, B.A., Cambardella, C.A., Chapin, F.S., Field, C.B., Holland, E.A., Mooney, H.A., 2001. Contrasting effects of elevated CO<sub>2</sub> on old and new soil carbon pools. *Soil Biol. Biochem.* 33, 365–373.
- Chander, K., Goyal, S., Mundra, M.C., Kapoor, K.K., 1997. Organic matter, microbial biomass and enzyme activity of soils under different crop rotations in the tropics. *Biol. Fert. Soils* 24, 306–310.
- Cong, R.H., Wang, X.J., Xu, M.G., Zhang, W.J., Xie, L.J., Yang, X.Y., Huang, S.M., Wang, B.R., 2012. Dynamics of soil carbon to nitrogen ratio changes under long-term fertilizer addition in wheat-corn double cropping systems of China. *Eur. J. Soil Sci.* 63, 341–350.
- Curtin, D., Wang, H., Selles, F., McConkey, B.G., Campbell, C.A., 2000. Tillage effects on carbon fluxes in continuous wheat and fallow-wheat rotations. *Soil Sci. Soc. Am. J.* 64, 2080–2086.
- Davidson, E.A., Belk, E., Boone, R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Global Change Biol.* 4, 217–227.
- Ding, W., Meng, L., Yin, Y., Cai, Z., Zheng, X., 2007. CO<sub>2</sub> emission in an intensively cultivated loam as affected by long-term application of organic manure and nitrogen fertilizer. *Soil Biol. Biochem.* 39, 669–679.
- Ding, W., Yu, H., Cai, Z., Han, F., Xu, Z., 2010. Responses of soil respiration to N fertilization in a loamy soil under maize cultivation. *Geoderma* 155, 381–389.
- Drewitt, G.B., Black, T.A., Nesic, Z., Humphreys, E.R., Jork, E.M., Swanson, R., Ethier, G.J., Griffis, T., Morgenstern, K., 2002. Measuring forest floor CO<sub>2</sub> fluxes in a Douglas-fir forest. *Agric. Forest Meteorol.* 110, 299–317.
- FAO, 1988. *World reference base for soil resources 1988-A framework for international classification, correlation and communication 103*. World Resources Reports, Rome, Italy.
- Gallardo, A., Schlesinger, W.H., 1994. Factors limiting microbial biomass in the mineral soil and forest floor of a warm-temperate forest. *Soil Biol. Biochem.* 26, 1409–1415.
- Gaumont-Guay, D., Black, T.A., Griffis, T.J., Barr, A.G., Jassal, R.S., Nesic, Z., 2006. Interpreting the dependence of soil respiration on soil temperature and water content in a boreal aspen stand. *Agric. Forest Meteorol.* 140, 220–235.
- Giardina, C., Binkley, D., Ryan, M., Fownes, J., Senock, R., 2004. Belowground carbon cycling in a humid tropical forest decreases with fertilization. *Oecologia* 139, 545–550.
- Johnston, A.E., Poulton, P.R., Coleman, K., 2009. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *Adv. Agron.* 101, 1–57.
- Kowalenko, C.G., Ivarson, K.C., Cameron, D.R., 1978. Effect of moisture content, temperature and nitrogen fertilization on carbon dioxide evolution from field soils. *Soil Biol. Biochem.* 10, 417–423.
- Kuzyakov, Y., Domanski, G., 2000. Carbon input by plants into the soil. *Review. J. Plant Nutr. Soil Sci.* 163, 421–431.
- La Scala, N., Marques, J., Pereira, G.T., Cora, J.E., 2000. Carbon dioxide emission related to chemical properties of a tropical bare soil. *Soil Biol. Biochem.* 32, 1469–1473.
- Li, H.J., Yan, J.X., Yue, X.F., Wang, M.B., 2008. Significance of soil temperature and moisture for soil respiration in a Chinese mountain area. *Agric. Forest Meteorol.* 148, 490–503.
- Li, X.D., Fu, H., Guo, D., Li, X.D., Wan, C.G., 2010. Partitioning soil respiration and assessing the carbon balance in a *Setaria italica* (L.) Beauv. Cropland on the Loess Plateau, Northern China. *Soil Biol. Biochem.* 42, 337–346.
- Li, Z.G., Zhang, R.H., Wang, X.J., Wang, J.P., Zhang, C.P., Tian, C.Y., 2011. Carbon dioxide fluxes and concentrations in a cotton field in northwestern China: effects of plastic mulching and drip irrigation. *Pedosphere* 21, 178–185.
- Liljeroth, E., Kuikman, P., van Veen, J.A., 1994. Carbon translocation to the rhizosphere of maize and wheat and influence on the turnover of native soil organic matter at different soil nitrogen levels. *Plant Soil* 161, 233–240.
- Lipiec, J., Arvidsson, J., Murer, E., 2003. Review of modelling crop growth, movement of water and chemicals in relation to topsoil and subsoil compaction. *Soil Till. Res.* 73, 15–29.
- Lu, R., 2000. *Analytical Methods of Soil Agricultural Chemistry*. China Agricultural Science and Technology Press, Beijing (in Chinese).
- Lu, R., Shi, Z., 2000. Rebuilding countermeasures and fertility properties for degenerative red soil hilly region. *Soil* 4, 198–209 (in Chinese).
- Mancinelli, R., Campiglia, E., Di Tizio, A., Marinari, S., 2010. Soil carbon dioxide emission and carbon content as affected by conventional and organic cropping systems in Mediterranean environment. *Appl. Soil Ecol.* 46, 64–72.

- Marinari, S., Mancinelli, R., Campiglia, E., Grego, S., 2006. Chemical and biological indicators of soil quality in organic and conventional farming systems in Central Italy. *Ecol. Indic.* 6, 701–711.
- Malhi, S.S., Nyborg, M., Solberg, E.D., McConkey, B., Dyck, M., Puurveen, D., 2011. Long-term straw management and N fertilizer rate effects on quantity and quality of organic C and N and some chemical properties in two contrasting soils in Western Canada. *Biol. Fertil. Soils*, <http://dx.doi.org/10.1007/s00374-011-0587-8>.
- Rochette, P., Flanagan, L.B., 1997. Quantifying rhizosphere respiration in a corn crop under field conditions. *Soil Sci. Soc. Am. J.* 61, 466–474.
- Schüller, W., Neubert, R., Levin, N., Fischer, N., Sonntag, C., 2000. Determination of microbial versus root-produced CO<sub>2</sub> in an agricultural ecosystem by means of δ<sup>13</sup>CO<sub>2</sub> measurements in soil air. *Tellus B* 52, 909–918.
- Schlesinger, W.H., Andrews, J.A., 2000. Soil respiration and the global carbon cycle. *Biogeochemistry* 48, 7–20.
- SPSS Inc., 1999. SPSS Base 17.0 for Windows User's Guide. SPSS Inc., Chicago, IL.
- Snyder, C.S., Brulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric. Ecosyst. Environ.* 113, 247–266.
- Tang, J., Qi, Y., Xu, M., Misson, L., Goldstein, A.H., 2005. Forest thinning and soil respiration in a ponderosa pine plantation in the Sierra Nevada. *Tree Physiol.* 25, 57–66.
- Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 37, 29–38.
- Xu, M., Qi, Y., 2001. Soil-surface CO<sub>2</sub> efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California. *Global Change Biol.* 7, 667–677.
- Yan, J.H., Zhang, D.Q., Zhou, G.Y., Liu, J.X., 2009. Soil respiration associated with forest succession in subtropical forests in Dinghushan Biosphere Reserve. *Soil Biol. Biochem.* 41, 991–999.
- Yang, L., Pan, J., Shao, Y., Chen, J.M., Ju, W.M., Shi, X., Yuan, S., 2007. Soil organic carbon decomposition and carbon pools in temperate and sub-tropical forests in China. *J. Environ. Manage.* 85, 690–695.
- Yi, Z.G., Fu, S.L., Yi, W.M., Zhou, G.Y., Mo, J.M., Zhang, D.Q., Ding, M.M., Wang, X.M., Zhou, L.X., 2007. Partitioning soil respiration of subtropical forests with different successional stages in south China. *Forest Ecol. Manage.* 243, 178–186.
- Yuste, J.C., Janssens, I.A., Carrara, A., Meiresonne, L., Ceulemans, R., 2003. Interactive effects of temperature and precipitation on soil respiration in a temperate maritime pine forest. *Tree Physiol.* 23, 1263–1270.
- Zhang, W.J., Xu, M.G., Wang, B.R., Wang, X.J., 2009. Soil organic carbon, total nitrogen and grain yields under long-term fertilizations in the upland red soil of southern China. *Nutr. Cycl. Agroecosyst.* 84, 59–69.
- Zinn, Y.L., Lal, R., Resck, D.V.S., 2005. Changes in soil organic carbon stocks under agriculture in Brazil. *Soil Till. Res.* 84, 28–40.