Soil $\text{CO}_2$ Emissions as Affected by 20-Year Continuous Cropping in Mollisols

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Abstract

Long-term continuous cropping of soybean ($Glycine\ max$), spring wheat ($Triticum\ aestivum$) and maize ($Zea\ mays$) is widely practiced by local farmers in northeast China. A field experiment (started in 1991) was used to investigate the differences in soil carbon dioxide ($\text{CO}_2$) emissions under continuous cropping of the three major crops and to evaluate the relationships between $\text{CO}_2$ fluxes and soil temperature and moisture for Mollisols in northeast China. Soil $\text{CO}_2$ emissions were measured using a closed-chamber method during the growing season in 2011. No remarkable differences in soil organic carbon were found among the cropping systems ($P>0.05$). However, significant differences in $\text{CO}_2$ emissions from soils were observed among the three cropping systems ($P<0.05$). Over the course of the entire growing season, cumulative soil $\text{CO}_2$ emissions under different cropping systems were in the following order: continuous maize ($\left(829\pm10\right)\ g\ \text{CO}_2\ m^{-2}$)$>$continuous wheat ($\left(629\pm22\right)\ g\ \text{CO}_2\ m^{-2}$)$>$continuous soybean ($\left(474\pm30\right)\ g\ \text{CO}_2\ m^{-2}$). Soil temperature explained 42-65% of the seasonal variations in soil $\text{CO}_2$ flux, with a $Q_{10}$ between 1.63 and 2.31; water-filled pore space explained 25-47% of the seasonal variations in soil $\text{CO}_2$ flux. A multiple regression model including both soil temperature ($T$, °C) and water-filled pore space ($W$, %), $\log(f)=a+bT\log(W)$, was established, accounting for 51-66% of the seasonal variations in soil $\text{CO}_2$ flux. The results suggest that soil $\text{CO}_2$ emissions and their $Q_{10}$ values under a continuous cropping system largely depend on crop types in Mollisols of Northeast China.

Key words: $\text{CO}_2$ flux, monocultures, soil organic carbon, temperature sensitivity, water-filled pore space

INTRODUCTION

Maintenance of soil organic carbon (SOC) is critical not only to maintain soil fertility and further crop yield but also for environmental sustainability in agroecosystems (Lal 2004; Singh et al. 2009). Soil organic carbon can be either a source or a sink of atmospheric carbon dioxide ($\text{CO}_2$), and its function in carbon cycling plays a crucial role in global climate change (Lal 2004). Thus, the sequestration of carbon into soils has been of increasing concern, and serves as one of the strategies to offset anthropogenic $\text{CO}_2$ (Ussiri and Lal 2009; Conant et al. 2011). However, the change in SOC occurs slowly and is relatively small in comparison with the vast background of SOC (Varvel 2006; Purakayastha et al. 2008; Lou et al. 2011a); therefore, measuring soil $\text{CO}_2$ emissions has been widely performed to evaluate the change in SOC in response to agricultural management practices (Jabro...
et al. 2008; Wang et al. 2013).

Agricultural management practice has been suggested as an important factor controlling soil carbon in agroecosystems (Sombrero and de Benito 2010; Lou et al. 2011b; Scheer et al. 2011). As one of the most common agricultural practices, crop rotation plays a significant role in impacting soil carbon (Lal 2004). Previous studies have suggested that increases in carbon sequestration can be achieved by changing from continuous monoculture to a crop rotation system (West and Post 2002; Jarecki and Lal 2003; González-Sánchez et al. 2012). In Northeast China, however, long-term continuous cropping has been widely adopted by local farmers due to the relatively low costs of continuous monoculture in field management. Moreover, information about soil CO2 emissions and the effect of continuous monocultures on the extensive Mollisols in Northeast China is limited (Kou et al. 2012).

In addition to management practices, soil micro-climate, such as soil temperature and moisture, can influence soil CO2 emissions (Bauchmann 2000; Bauer et al. 2008; Fiener et al. 2012; Xue et al. 2012). However, models of the relationships between soil micro-climate factors and soil CO2 fluxes are still inexact, particularly for the relationship between soil moisture and CO2 fluxes. The disparities among trials may be collectively caused by soil types (Gao et al. 2011), modeling equations and parameters (Davidson et al. 2000; Jia et al. 2006), and methods for measuring or modeling CO2 emissions (Herbst et al. 2009; de Bortoli Teixeira et al. 2011; Emran et al. 2012). In addition, soil temperature and moisture likely have a confounding effect on soil CO2 fluxes (Davidson et al. 1998; Iqbal et al. 2008; Almagro et al. 2009).

Because approaching a new equilibrium is slow after changed environmental conditions, the effects of cropping regimes on soil carbon dynamic should be studied through long-term field experiments. Therefore, using a long-term continuous cropping experiment, we investigated the impacts of continuous monocultures of three main crops (soybean, Glycine max; spring wheat, Triticum aestivum; and maize, Zea mays) in Northeast China on SOC content and soil CO2 emissions. The specific objectives were to estimate soil CO2 emissions as influenced by different cropping regimes and to quantify the seasonal variations in soil CO2 fluxes in relation to soil temperature and moisture.

RESULTS

Soil properties, grain yield, and biomass

No significant differences in SOC content were observed among the three continuous cropping systems (P>0.05; Table 1). Slight but significantly lower total nitrogen (TN) content and soil pH values were observed under the continuous maize cropping system compared with the soybean monoculture (P<0.05; Table 1).

The continuous maize monoculture had the highest biomass of straw, root, and crop grain among the three cropping systems. Compared with the soybean monoculture, the root biomass under the cropping systems of continuous wheat and maize was significantly higher by 235 and 100%, respectively (both P<0.05; Table 1).

Soil temperature and moisture

Soil temperature varied from 4.7 to 35.3°C during the course of the sampling period, with averages of 22.2 and 18.9°C at depths of 5 and 10 cm, respectively (Fig. 1-A and B). Soil temperature at both the 5 and 10 cm depths reached a maximum on June 24 (Fig. 1- A and B). There was no significant difference in the seasonal averages of soil temperature at the 5 and 10 cm depths among treatments (Fig. 1-A and B). Soil moisture ranged from 20 to 60% of water-filled pore space (WFPS) during the whole sampling period, with an average of 42% WFPS (Fig. 1-C). A significantly

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SOC (mg g⁻¹)</th>
<th>TN (mg g⁻¹)</th>
<th>pH</th>
<th>Grain (g m⁻²)</th>
<th>Straw (g m⁻²)</th>
<th>Root (g m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean</td>
<td>30.53 (0.11) a</td>
<td>2.23 (0.01) a</td>
<td>5.47 (0.11) a</td>
<td>153 (12) b</td>
<td>145 (7) c</td>
<td>17 (1) c</td>
</tr>
<tr>
<td>Wheat</td>
<td>30.19 (0.26) a</td>
<td>2.28 (0.01) a</td>
<td>5.40 (0.03) ab</td>
<td>172 (14) b</td>
<td>281 (13) b</td>
<td>34 (7) b</td>
</tr>
<tr>
<td>Maize</td>
<td>29.45 (0.23) a</td>
<td>2.14 (0.02) b</td>
<td>5.09 (0.09) b</td>
<td>659 (42) a</td>
<td>434 (41) a</td>
<td>57 (6) a</td>
</tr>
</tbody>
</table>

Values in parentheses are SE (n=3). Letters following the means in columns indicate a significant different at P<0.05.
higher seasonal average of soil WFPS was observed under the continuous maize cropping system compared with the soybean or wheat monoculture \((P<0.05;\) Fig. 1-C).

The mean soil \(\text{CO}_2\) flux in the continuous maize cropping system was higher by 23 and 42\% compared with those in the continuous wheat and soybean monocultures, respectively (both \(P<0.05\)).

Cumulative \(\text{CO}_2\) emissions during the entire sampling season in the continuous soybean, wheat, and maize systems were estimated to be \((474\pm30)\), \((629\pm22)\), and \((829\pm10)\ \text{g CO}_2\ \text{m}^{-2}\), respectively (Fig. 2-B). Soils in the continuous maize and wheat monoculture emitted 75 and 33\% more \(\text{CO}_2\) than the soybean monoculture \((P<0.05;\) Fig. 2-B).

Soil \(\text{CO}_2\) emissions

Seasonal variations in soil \(\text{CO}_2\) fluxes are summarized in Fig. 2-A. Soil \(\text{CO}_2\) fluxes increased gradually from the beginning of the experiment, reached maximum levels between July 15 and August 6, and then declined gradually until the end of September (Fig. 2-A). The mean soil \(\text{CO}_2\) flux in the continuous maize cropping system was higher by 23 and 42\% compared with those in the continuous wheat and soybean monocultures, respectively (both \(P<0.05\)).

Cumulative \(\text{CO}_2\) emissions during the entire sampling season in the continuous soybean, wheat, and maize systems were estimated to be \((474\pm30)\), \((629\pm22)\), and \((829\pm10)\ \text{g CO}_2\ \text{m}^{-2}\), respectively (Fig. 2-B). Soils in the continuous maize and wheat monoculture emitted 75 and 33\% more \(\text{CO}_2\) than the soybean monoculture \((P<0.05;\) Fig. 2-B).

Relations between soil \(\text{CO}_2\) fluxes and soil micro-climate factors

Regression analyses showed a poor relationship between soil \(\text{CO}_2\) flux and soil temperature during the full sampling periods (Table 2). The relationship fit well using an exponential model only for samples at a depth of 10 cm under wheat monoculture \((R^2=0.23, P<0.05, n=18;\) Table 2). However, excluding the initial five data sets greatly improved the relationships

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between soil CO$_2$ fluxes and soil temperature for both layers under the three monoculture systems (Table 2). The exponential model explained 42-65% of the seasonal variations in soil CO$_2$ fluxes ($P<0.05$, n=13), and the temperature sensitivity ($Q_{10}$) ranged between 1.63 and 2.31 (Table 2).

After the first five samples were excluded, the relationship between soil CO$_2$ fluxes and soil WFPS could also be fitted by an exponential model with an improved $R^2$, which explained 25-47% of the seasonal variations in soil CO$_2$ fluxes ($P<0.10$; Table 3). Additionally, a log-transformed multiple regression model, $\log(f)=a+bT\log(W)$, including both soil temperature and soil WFPS, accounted for 51-66% of the seasonal variations in soil CO$_2$ fluxes for the three cropping systems ($P<0.01$; Table 3).

**DISCUSSION**

Effects of long-term cropping regimes on SOC and CO$_2$ emissions

The lack of significant differences in the SOC content among the three continuous cropping systems in the present study (Table 1) is inconsistent with another study on the effects of long-term cropping regimes on soil carbon (Kou et al. 2012). Kou et al. (2012) observed a higher increase in SOC levels in the topsoil under continuous maize monoculture compared with continuous soybean, suggesting a greater potential of carbon sequestration under the continuous maize monoculture. The amount of carbon sequestration is dependent on the level of applied organic amendments (Diacono and Montemurro 2010) and on the amount of carbon which is already in the soil (Six et al. 2002). Thus, the disparities between the results might partially originate from the differences in the applied fertilizers. Organic manure combined with inorganic fertilizer was applied in the study by Kou et al. (2012), whereas the plots in our present study were treated with inorganic fertilizer alone. On the other hand, the negligible differences in SOC among the cropping systems could be partially attributed to the relatively minor change in SOC induced by cropping regimes compared to the large carbon background of the Mollisols. Therefore, it is necessary to measure soil CO$_2$ emissions in order to evaluate carbon loss in response to cropping regimes.

Carbon dioxide emission from soils is the product of root and soil microbial respiration (Kuzyakov 2006). Although root respiration is an important contributor to total soil CO$_2$ emissions in situ (Raich and Tufekcioglu 2000), there are large discrepancies regarding the contribution of roots to total soil respiration in agroecosystems (Raich and Mora 2005; Singh et al. 2009). The root contribution to soil CO$_2$ emissions was estimated to be as high as 48% or as low as 12% of the total (Raich and Tufekcioglu 2000; Kuzyakov and Larionova 2005). The disparities between the trials may be collectively caused by environmental

### Table 2 Relationship between soil CO$_2$ flux ($f$) and soil temperature ($T$) at depths of 5 and 10 cm under different continuous cropping systems

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Depth (cm)</th>
<th>Total experiment period (May 27-Sep. 30, 2011, n=18)</th>
<th>From July 1 to the end of the experiment (July 1-Sep. 30, 2011, n=13)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation</td>
<td>$R^2$</td>
<td>$Q_{10}$</td>
</tr>
<tr>
<td>Soybean</td>
<td>5</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-</td>
<td>0.08</td>
</tr>
<tr>
<td>Wheat</td>
<td>5</td>
<td>-</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>$f=76.427\exp(0.0408T)$</td>
<td>0.23$^*$</td>
</tr>
<tr>
<td>Maize</td>
<td>5</td>
<td>-</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.03</td>
<td>-</td>
</tr>
</tbody>
</table>

$^*$, **, and *** indicate significance at $P<0.05$, 0.01, and 0.001, respectively. The same as below.

$^*$, the regression equation was not established due to low $R^2$.

### Table 3 The relationship between soil CO$_2$ flux ($f$) and soil water-filled pore space ($W$, WFPS) and the combination of soil temperature ($T$) and WFPS under different continuous cropping systems (n=13)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>With soil WFPS ($R^2$)</th>
<th>With T combined with soil WFPS ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean</td>
<td>$f=22.758\exp(0.0464W)$</td>
<td>0.47$^*$</td>
</tr>
<tr>
<td>Wheat</td>
<td>$f=15.810\exp(0.0562W)$</td>
<td>0.25$^*$</td>
</tr>
<tr>
<td>Maize</td>
<td>$f=17.013\exp(0.0598W)$</td>
<td>0.47**</td>
</tr>
</tbody>
</table>

$^*$ indicates significance at $P=0.05-0.10$ level.
Soil CO$_2$ emissions were affected by 20-year continuous cropping in Mollisols. Generally, soil temperature and moisture have been identified as the main factors influencing the seasonal dynamics of soil respiration in short timescales. In our study, the influence of long-term cropping on soil CO$_2$ emissions was dependent upon crop types. Cumulative soil CO$_2$ emissions under different cropping systems followed the order of maize > wheat > soybean (Fig. 2-B). A previous study conducted in Central Iowa showed that the increased soil CO$_2$ emission from continuous maize plots was due to increased crop residue incorporation compared to other cropping systems (Wilson and Al-Kaisi 2008). In the present study, straw was removed from fields after harvest for all treatments, and there was no crop straw incorporation into the soils. Thus, the residue incorporation into the soil was mainly from root biomass. The significant positive correlation between cumulative CO$_2$ emissions and root biomass, but not SOC (data not shown), combined with the significant difference in root biomass among treatments (Table 1), indicated that the observed higher CO$_2$ emissions from the continuous maize cropping plots (Fig. 2-B) can be mainly attributed to the autotrophic respiration of the roots compared to the other two cropping systems.

In addition to root respiration, soil microorganisms are considered to be another important contributor to soil CO$_2$ emissions due to their key roles in transforming native and/or exogenous organic matter (Kuzyakov 2006; Singh et al. 2009). The presence of roots can greatly affect the rate of soil organic matter decomposition in the rhizosphere by changing microbial activity, which is known as a “rhizosphere priming effect”, representing the interaction between the growing roots and decomposition of soil organic matter (Kuzyakov 2006). In the present study, although there was no significant difference in SOC content among the cropping systems ($P > 0.05$), a remarkable difference in root biomass was observed ($P < 0.05$; Table 1). Therefore, a positive priming effect induced by the higher root biomass in the continuous maize cropping system might cause a higher rate of decomposition of “old” carbon and thus higher heterotrophic soil respiration compared with the continuous soybean and wheat systems.

Effects of soil temperature and moisture on CO$_2$ emissions

Generally, soil temperature and moisture have been identified as the main factors influencing the seasonal dynamics of soil respiration in short timescales. In the present study, the influence of long-term cropping on soil CO$_2$ emissions was dependent upon crop types. Cumulative soil CO$_2$ emissions under different cropping systems followed the order of maize > wheat > soybean (Fig. 2-B). A previous study conducted in Central Iowa showed that the increased soil CO$_2$ emission from continuous maize plots was due to increased crop residue incorporation compared to other cropping systems (Wilson and Al-Kaisi 2008). In the present study, straw was removed from fields after harvest for all treatments, and there was no crop straw incorporation into the soils. Thus, the residue incorporation into the soil was mainly from root biomass. The significant positive correlation between cumulative CO$_2$ emissions and root biomass, but not SOC (data not shown), combined with the significant difference in root biomass among treatments (Table 1), indicated that the observed higher CO$_2$ emissions from the continuous maize cropping plots (Fig. 2-B) can be mainly attributed to the autotrophic respiration of the roots compared to the other two cropping systems.

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upper 10 cm are likely to lead to an underestimation of temperature sensitivity (Graf et al. 2008). Thus, the $Q_{10}$ values of soil respiration at a depth of 10 cm might be more accurate than those at a depth of 5 cm.

Similarly, the relationship between soil CO$_2$ fluxes and soil WFPS was also fitted with an exponential model after exclusion of the first five samples (Table 3). We also attributed this result to the root growth or soil disturbance due to ploughing or the application of chemical fertilizer. Furthermore, the multiple regression model including both soil temperature and WFPS (Table 3) revealed a collective impact of soil temperature and moisture on soil CO$_2$ emissions from the Mollisols.

CONCLUSION

No remarkable differences in SOC were observed after 20 yr of continuous maize, soybean, and wheat cropping. Although there were no differences in SOC, significant differences in soil CO$_2$ emissions were observed among the three cropping systems. The influences of soil temperature and WFPS on soil CO$_2$ fluxes could be described well using an exponential equation model. The $Q_{10}$ values ranged between 1.63 for soybean and 2.31 for maize at a depth of 5 cm depth. A log-transformed multiple regression model including both soil temperature and moisture accounted for 51-66% of the seasonal variations in soil CO$_2$ fluxes. Our results suggest that soil CO$_2$ emissions and $Q_{10}$ values from continuous cropping systems largely depend on crop types in Mollisols of northeast China.

MATERIALS AND METHODS

Site description and experimental design

The field experiment was carried out at the Hailun National Experiment Station of Agroecosystem of the Chinese Academy of Sciences, located in Hailun County, Heilongjiang Province (47°26´N, 126°38´E), in the growing season between late spring and early autumn in 2011. The region has a typical temperate continental monsoon climate, characterized by hot summers and cold winters. The mean annual temperature was 1.5°C, and the lowest and highest mean monthly values were detected in January (-23°C) and in July (21°C), respectively. The mean annual precipitation was 550 mm, more than 80% of which occurred from May to September. The frost-free period was approximately 120 d. The soil type is loamy loess and is classified as a Mollisol (Typic Hapludoll).

A long-term continuous cropping experiment was established in a completely randomized block design in 1991. The experiment included three replicates of three treatments: continuous monocultures of soybean, wheat, and maize. Each block covered 77 m$^2$, with 10 rows in each block, and was separated by a 0.7-m buffer strip. The fertilizer applications were as follows: 27 kg N ha$^{-1}$ and 69 kg P ha$^{-1}$ for soybean; 92 kg N ha$^{-1}$ and 39 kg P ha$^{-1}$ for wheat; 131 kg N ha$^{-1}$ and 69 kg P ha$^{-1}$ for maize. Fertilizers N and P were applied in the form of urea and diammonium phosphate, respectively. For urea application, two splits were adopted, with the treatments receiving N fertilizer as the basal (May 10) and supplementary (June 22) fertilizers at a ratio of 1:1 for continuous maize cropping. The crop straw was removed after harvest under all treatments, following the common practice of local farmers. The soil was manually tilled to a depth of 15 to 20 cm after harvest.

Soil CO$_2$ flux measurement

Soil CO$_2$ emission was sampled using a closed-chamber followed by gas chromatography. Three chambers (0.7 m$^2$ × 0.2 m × 0.25 m) were laid within each treatment. Air samples were manually collected using a 20-mL syringe from a septum installed at the top of the chamber at 0, 10, 20, and 30 min after closure, and then injected into pre-evacuated 18-mL vials and taken to the laboratory for analysis. Gas sampling was performed between 9:00 and 11:00 a.m. once per week, except on July 30th due to crop lodging resulting from heavy rainfall. Carbon dioxide was collected from the whole soil including rhizosphere and bulk soil (i.e., rhizosphere respiration and native soil respiration).

Sample CO$_2$ concentration was determined with a gas chromatograph (GC-2010, Shimadzu Corp., Japan) equipped with a flame ionization detector. The increased rate of CO$_2$ concentration vs. time in the chamber air was calculated by linear regression analysis. All linear regression values of $R^2$ were larger than 0.90.

Carbon dioxide flux was computed from the rate of the change in chamber CO$_2$ concentration vs. time, chamber volume V and soil surface area A using the following formula:

$$f = \frac{\rho \times \Delta c / \Delta t \times V}{A \times 273/(273+T)}$$

Where, $f$ is the soil CO$_2$ flux in mg CO$_2$ m$^{-2}$ h$^{-1}$, $\rho$ is the CO$_2$ density under standard conditions, $\Delta c / \Delta t$ is the linear change in CO$_2$ concentration inside the chamber and $T$ is the temperature inside the chamber. Cumulative soil CO$_2$ emission (g CO$_2$ m$^{-2}$) during the entire sampling season was calculated by summing the products of the (averaged) two neighboring fluxes, multiplied by their interval time.

The air temperature inside the chamber was recorded with
an Hg thermometer. Soil temperatures at vertical depths of 5- and 10-cm were measured in situ using a geothermometer simultaneous to the gas sampling. Field soil water content was determined by a gravimetric method. Soil bulk density was also gravimetrically determined from undisturbed soils within 1 m of the field chambers. Soil WFPS was used as the moisture variable in all analyses, as this property integrates porosity and moisture variables (Franzluebbers 1999). Values of the gravimetric soil moisture were converted to soil WFPS values using the following equation:

\[
\text{WFPS} = \left( \frac{\theta_s \times \text{sbd} \times 100\%}{(1 - (\text{sbd} / \text{spd}))}\right)
\]

Where, \( \theta_s \) is gravimetric soil moisture (kg water kg\(^{-1}\) soil), \( \text{sbd} \) is soil bulk density (Mg m\(^{-3}\) soil) and \( \text{spd} \) is soil particle density.

### Soil sampling and analyses, and biomass determination

Soil samples were collected in early October 2011. Eight soil samples (0-20 cm) were randomly collected within each block and then mixed thoroughly to form a composite for analyses of SOC, TN, and soil pH. Air-dried soil samples (<2 mm) were used to determine soil pH in a 1:2.5 (w/v) soil to water ratio. Soil organic C and TN concentrations were analyzed using an elemental analyzer (Vario EL III, Elementar, Germany).

Soybean and maize were planted in early May and harvested in late September; wheat was directly sown in April and harvested in July, 2011. All aboveground crop materials within a plot area of 2 m\(^2\)×1.4 m were cut in each block. Root biomass (0-20 cm) was measured in the same location used for aboveground sampling. Roots were separated from soils by picking and washing. All crop samples (grain, straw and root) were oven-dried at 70°C for 48 h and then weighed.

### Calculations

The response of soil CO\(_2\) flux to soil temperature was described by an exponential function:

\[
f = \theta_s \times \text{sbd} \times 100\% / (1 - (\text{sbd} / \text{spd}))
\]

Where, \( f \) is the soil CO\(_2\) flux (mg CO\(_2\) m\(^{-2}\) h\(^{-1}\)) at soil temperature \( T \), and \( a \) and \( b \) are regression coefficients. The temperature sensitivity (\( Q_{10} \)) was defined as the difference in soil respiration rate over a 10°C increment, was calculated by the following first-order exponential function:

\[
Q_{10} = e^{10b}
\]

### Statistical analyses

Homogeneity of variance and normality tests were carried out on gas and biomass data. A one-way analysis of variance (ANOVA) following the least significant difference (LSD) was used to test the differences in SOC content, biomass, and cumulative CO\(_2\) emissions among treatments. Regression analysis was used to determine the relationships between soil environmental parameters (soil temperature, soil moisture, and soil temperature combined with soil moisture) and soil CO\(_2\) fluxes. All statistical analyses were conducted using SPSS 13.0 for Windows (SPSS Inc, Chicago, IL).

### Acknowledgements

This work was supported by the Key Research Program of the Chinese Academy of Sciences (KZZD-EW-TZ-16-02), the Foundation for Young Talents of the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences (DLSYQ13001), and the National Natural Science Foundation of China (41101283). We thank Ms. Sun Guidan for laboratory assistance and Ms. Gao Weili and Wen Xiuling for participation in the field sampling.

### References


Sombrero A, de Benito A. 2010. Carbon accumulation in


(Managing editor SUN Lu-juan)