Soil respiration, glomalin content, and enzymatic activity response to straw application in a wheat-maize rotation system

Article *in* Journal of Soils and Sediments · August 2017

DOI: 10.1007/s11368-017-1817-y

Guopeng Liang

Northern Arizona University

6 PUBLICATIONS **8** CITATIONS

Huijun wu

Chinese Academy of Agricultural Sciences

19 PUBLICATIONS **293** CITATIONS

J Soils Sediments
DOI 10.1007/s11368-017-1817-y

SOILS, SEC 1 • SOIL ORGANIC MATTER DYNAMICS AND NUTRIENT CYCLING • RESEARCH ARTICLE

Soil respiration, glomalin content, and enzymatic activity response to straw application in a wheat-maize rotation system

Guopeng Liang[1,2] · Huijun Wu[1] · Albert A. Houssou[1] · Dianxiong Cai[1] · Xueping Wu[1] ·
Lili Gao[1] · Bisheng Wang[1] · Shengping Li[1]

Received: 26 May 2017 / Accepted: 16 August 2017

Abstract

Purpose Straw residue has been widely applied in the North China Plain agroecosystems due to their positive roles in soil fertility improvement, sustainable production, and climate change mitigation. However, little is known about how straw application alters soil respiration by influencing soil biochemical properties in this region. This is the first study to evaluate the role of soil enzyme activity and glomalin content in the response of soil respiration to straw application at different growth stages in a wheat-maize rotation system.

Materials and methods Field experiment was conducted in a wheat-maize rotation system and it contained two treatments: straw residue removal (CK) and straw residues application (SR). Soil respiration, moisture, and temperature were measured using LI-8100 at different growth stages during wheat and maize (2013–2015) growing seasons. From 2013 to 2014, soil sample (0–20 cm) was collected at different growth stages during wheat and maize growing seasons and transported to the laboratory. Glomalin content and soil enzyme activity were analyzed by using Bradford and enzyme-labeled meter method, respectively. In addition, we determined soil chemical properties such as soil organic carbon (SOC), soil total N content (TN), ammonium N (NH_4^+-N), and nitrate N (NO_3^--N) concentrations.

Results and discussion SR significantly increased soil respiration and this promotion effect became more significant after 4-year straw application. Soil respiration exhibited significant seasonal variation and was significantly increased by soil temperature with Q_{10} ranging from 1.73 to 2.14 for CK and from 1.51 to 2.28 for SR. Both soil temperature and moisture accounted for 70–72% of the seasonal variation in soil respiration. SR significantly increased easily extractable glomalin-related soil protein during 2013–2014 wheat growing season except jointing stage. In addition, positive and significant effect of SR on activities of β-glucosidase and cellobiohydrolase was observed at initial and vigorous growth stages. Straw application significantly increased TN, but did not significantly influence SOC, NH_4^+-N, and NO_3^--N concentrations.

Conclusions Our study demonstrated that straw application increased soil respiration by stimulating soil enzyme activities and improving easily extractable glomalin-related soil protein. Straw application is recommended as an agricultural management in the North China Plain because of its role in improving biochemical properties. To improve soil biochemical parameters with a relative low soil respiration rate, further information is necessary about the optimum amount of straw application.

Keywords Glomalin · Seasonal variation · Soil enzymatic activities · Soil respiration · Straw residues

---

Responsible editor: Zucong Cai

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11368-017-1817-y) contains supplementary material, which is available to authorized users.

✉ Huijun Wu
hjwu@caas.ac.cn

[1] National Engineering Laboratory for Improving Quality of Arable Land, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

[2] Department of Microbiology and Plant Biology, University of Oklahoma, Norman 73019, OK, USA

1 Introduction

Over the past century, CO_2 concentration in the atmosphere has increased more than 40% (IPCC 2013). As a major process of soil carbon output, soil respiration has a significant impact on atmospheric CO_2. It can emit 98 ± 12 pg C to the atmosphere every year (Bond-Lamberty and Thomson 2010), which is more than 10 times the current rate of fossil fuel combustion (Hashimoto 2012). Understanding controls on soil respiration in cropland is crucial because relatively minor changes in respiration rates may have a great effect on the future atmospheric CO_2 concentrations (Chen et al. 2011).

As a common agricultural management, straw application affects soil respiration by altering soil physical properties such as soil aeration, soil moisture, and temperature (Meng et al. 2005). These soil physical parameters have a significant effect on soil enzyme activity and the processes that decompose straw residues to soil organic matter and CO_2 (Franzluebbers et al. 1995). Previous studies have demonstrated that soil temperature and moisture remain dominating among all the factors controlling soil respiration (Rey et al. 2011; Wang et al. 2014b). The exponential relationship between soil respiration and temperature has been reported (Thomas and Hoon 2010; Darenova et al. 2014; Liang et al. 2015), whereas the effects of soil moisture on soil respiration are not always consistent (Davidson et al. 2000; Wang et al. 2014a, b).

Burning has been widely adopted by farmers as an easy and cheap way that removes straw residues after harvests in some region of North China Plain. This management is not beneficial to agricultural sustainable development and can increase CO_2 emissions. According to some studies, straw application has a positive impact on soil organic carbon (SOC) stocks (Mahmoodabadi and Heydarpour 2014; Khaliq and Abbasi 2015), which contributes to promote soil carbon sequestration and mitigate CO_2 concentrations. This positive effect can be significant after many years of straw application (Lou et al. 2011). In addition, straw application also can significantly increase nitrogen content in soils and then improve crop productivity (Lou et al. 2011).

In addition to improving soil chemical properties, straw application is a good agricultural management that is beneficial to soil biological parameter improvement. Both glomalin content and enzymatic activity are good indicators of soil biological conditions (Gispert et al. 2013). Glomalin, a glycoprotein produced by arbuscular mycorrhizal fungi (AMF), contributes to the preservation of organic carbon in the soil (Rilling et al. 2001). Glomalin content was responsive, even in the short term, to agronomic management practices (Wright and Anderson 2000). Zhang et al. (2014) reported that glomalin content could be increased by the application of straw residues. Soil enzymes are mainly derived from soil microorganisms; they mediate the transformation of elements in the soil into forms required for plant growth and control the rate of soil nutrient cycling. Soil enzymes could act as indicators of soil microbiological characteristics, and therefore soil enzymatic activities are very important in detecting soil biological quality and predicting carbon cycle in the future (Allison et al. 2008; Allison et al. 2010). Some soil enzymes such as β-glucosidase (BG) and cellobiohydrolase (CBH) were reported to be specific for the degradation of soil organic matter (Li et al. 2009; Stott et al. 2010). Many studies found that the activities of BG and CBH significantly increased after straw application (Dash et al. 2014; Chen et al. 2015).

The application of straw residues has been widely used in the North China Plain agroecosystems recently due to their positive roles in soil fertility improvement, sustainable production, and climate change mitigation. Even though several studies about the response of soil respiration to straw application have been done, most of these studies focused on how straw application influenced soil respiration by changing plant biomass (Li et al. 2013). Very limited numbers of paper explored the mechanism that straw application altered soil respiration by changing soil enzyme activity. However, these researches only measured soil enzyme activity for one time and tried to find the relationship between soil enzyme activity and respiration (Tejada and Benitez 2014). In theory, the mechanism about how straw application influences soil respiration by changing soil enzyme activity should be not the same at different growth stages. To the best of our knowledge, this study is the first one to evaluate the role of soil enzyme activity and glomalin content in the response of soil respiration to straw application at different growth stages in a wheat-maize rotation system. A field experiment was conducted to answer the following questions: (i) how is the seasonal variation of soil respiration and its relationship with soil temperature and moisture? (ii) could application of straw residues significantly influence soil respiration? (iii) could straw application significantly improve soil biochemical properties (glomalin, soil enzymatic activity, available N, SOC, and TN)? and (iv) what is the mechanism about how straw application influences soil respiration by changing soil enzyme activity and glomalin content?

2 Materials and methods

2.1 Experimental site

This study was conducted for wheat-maize rotation system at Agricultural Station of Chinese Academy of Agricultural Sciences (39° 36′ N, 116° 36′ E) in 2010. This site is at an elevation of about 18 m above sea level and is located in Hebei Province, China. The climate is typical temperate continental monsoon and annual average temperature is 11.9 °C, with the mean monthly lowest and highest values occurring in January and July, respectively. The mean annual precipitation is

550 mm, with 80% falling between June and September. The soil taxonomy is silt loam according to the FAO soil classification system (World Reference Base for Soil Resources, 2006), with initial properties (0–20 cm) of 6.38 g kg^{-1} SOC, 0.85 g kg^{-1} TN, 12.75 mg kg^{-1} available P (Olsen method), 93.7 mg kg^{-1} available K (NH_4AC extraction, atomic absorption spectrophotometer (AAS) method), 22% soil water holding capacity, and pH (H_2O) 8.0.

2.2 Experimental design

Six plots (67 m^2 each), containing two treatments with three replicates, were established using a randomized block design in 2010. The treatments were straw residues removal (CK) and straw residues application (SR). For SR treatment, the smashed straw residues were directly returned to the field after wheat and maize harvest every year, and were incorporated into the soil with mouldboard plowing (about 20-cm depth). The dry weight basis amount of wheat (44.7% total C, 0.76% total N) and maize straw (38.6% total C, 0.92% total N) was about 3000 and 8000 kg ha^{-1}, respectively. Calcium superphosphate (150 kg P_2O_5 ha^{-1}) and potassium sulfate (75 kg K_2O ha^{-1}) were applied in the both CK and SR treatments before tillage. Winter wheat was sowed in October and harvested in June of the following year and summer maize was sowed in June after tillage and harvested in October.

2.3 Measurements of soil respiration

Soil respiration (in μmol CO_2 m^{-2} s^{-1}) was measured using a portable soil respiration system (LI-8100, Li-COR Inc., Lincoln, NE, USA) during wheat and maize (2013–2015) growing seasons. Table S1 (Electronic Supplementary Material) describes the specific dates of soil respiration measurement and their corresponding growth stages. The soil respiration chamber was mounted on a PVC soil collar that was sharpened at the bottom. Each PVC collar (10 cm in height, 20 cm in inner diameter) was inserted into the soil surface at a depth of 8 cm in each plot. Soil respiration was measured between 9:00 and 11:00 a.m. (local time). Soil temperature at 10 cm depth was simultaneously determined with soil respiration measurement using thermometer of Li-8100 and soil moisture at 10-cm depth was gravimetrically determined by oven-drying.

2.4 Soil sampling and analyses

From 2013 to 2014, three soil samples (0–20 cm) in each plot were randomly collected using a 3-cm-diameter soil corer during wheat (wintering, tillering, jointing, filling, and maturity stages) and maize (seedling, jointing, heading, filling, and maturity stages) growing season and then mixed thoroughly to form a composite. The fresh samples were stored immediately in sealed plastic bags and transported to the laboratory in an insulated container. After the visible stones, roots and other litter were removed by hand, soil samples were sieved (< 2 mm). Aliquots of the samples were then stored at room temperature until SOC, TN, and glomalin analysis, at 4 °C until soil enzymatic activities, NH_4^+-N and NO_3^--N concentrations analysis (within 1 week).

SOC and TN were measured using a CHN element analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). NH_4^+-N and NO_3^--N concentrations were determined by extracting the soil with 1 M KCl solution (1:5, *w*:*v*) for 60 min and then measuring the concentrations using a flow injection autoanalyzer (Seal Analytical GmbH, Noderstedt, Germany).

Glomalin in soil was quantified as glomalin-related soil protein (GRSP). Rosier et al. (2006) found that Bradford method can be useful in determining glomalin content when organic matter concentrations are low. In the cropland at Agricultural Station of Chinese Academy of Agricultural Sciences (Hebei Province) we studied, SOC and nutrients are generally low. Bradford method was also used to measure glomalin content in many recent straw application studies (Wu et al. 2011; Hu et al. 2014). Air-dry soil samples (< 2 mm) were added to 8 ml of 20 mM trisodium citrate dehydrate solution at pH 7.0 in centrifuge tube of 50 ml and then posed in autoclave at 121 °C for 30 min. After each extraction, the sample was centrifuged at 10,000*g* for 5 min and the supernatant containing glomalin was collected and stored at 4 °C to determine easily extractable glomalin-related soil protein (EEG). EEG content in the extract was determined by Bradford assay, using bovine serum albumin as a standard. Results were expressed as mg glomalin g^{-1} soil. The activities of BG and CBH were detected through enzyme-labeled meter method expressed by Ai et al. (2012). Specifically, 1.0 g dry mass of fresh soil was homogenized by using 100 ml sterilized water. The sterilized water, sample suspension, references (10 μM), and substrates (200 μM) were dispensed into the wells of a black 96-well microplate and then the microplates were incubated in the dark at 25 °C for 4 h. Fluorescence was quantified using a microplate fluorometer (Scientific Fluoroskan Ascent FL, Thermo,USA) with 365-nm excitation and 450-nm emission filters. The enzyme activities were expressed in units of nmol h^{-1} g^{-1}.

2.5 Statistical analysis

The response of soil respiration to soil temperature was described by an exponential function:

$$\mathrm{Rs} = ae^{\beta T} \qquad (1)$$

where Rs is soil respiration rate (μmol m^{-2} s^{-1}), and T is soil temperature (in °C) at 10 cm depth; a and β are constants.

The temperature sensitivity of soil respiration (Q_{10}), defined as the increment in soil respiration for every 10 °C of increase in soil temperature, was calculated as:

$$Q_{10} = e^{10\beta} \quad (2)$$

All the statistical analyses were performed by using SAS version 9.2. For each variable measured at different stages, the data were analyzed by one-sample *t* test using the least significant difference (LSD) test ($P < 0.05$) to make a comparison between CK and SR treatments. One-way ANOVA was applied to test the differences among growth stages for nitrogen variables and EEG. Pearson's correlation analyses were performed to assess the relationships between soil respiration and biochemical parameters.

3 Results

3.1 Seasonal patterns of soil respiration, moisture, and temperature

Soil moisture at 10-cm depth during wheat-maize growing season ranged from 8.7 to 21.4% under CK and from 8.6 to 21.5% under SR (Fig. 1a); no significant difference was observed between CK and SR ($p > 0.05$). Soil temperature under the two treatments showed strong seasonal variation, minimum soil temperature was observed on 26 November 2013 and maximum was observed on 10 and 25 June 2014 (Fig. 1b). Straw application did not significantly influence soil temperature.

Soil respiration under both CK and SR showed similar seasonal patterns, which indicated seasonal patterns of soil respiration were not significantly influenced by straw residues and generally corresponded to the seasonal variations of soil temperature (Fig. 1b, c). During 2013–2014 wheat growing season, soil respiration under CK and SR decreased from 29 October 2013 (seedling stage) and reached minimum values (0.61 μmol m^{-2} s^{-1} for CK and 0.66 μmol m^{-2} s^{-1} for SR) on 13 March 2014 (tillering stage), followed by an increase at the mid of April 2014 (jointing stage), reached maximum values on 18 May 2014 (filling stage) and decreased again on 7 June 2014 (maturity stage). During 2014 maize growing season, soil respiration under the two treatments ranged from 1.35 to 5.59 μmol m^{-2} s^{-1}. It increased gradually from 10 July 2014 (seedling stage) and peaked on 15 August 2014 (heading stage), and then decreased sharply until maturity stage. Seasonal patterns of soil respiration during 2014–2015 wheat and maize growing season were similar with those of soil respiration during 2013–2014 wheat and maize growing season.

Significant and positive effect of straw residues on soil respiration was found during 2013–2014 wheat growing season (seedling and wintering stages), 2014 maize growing season (heading and filling stages), 2014–2015 wheat growing season except maturity stage, and 2015 maize growing season (seedling, jointing, and heading stages) (Fig. 1c).

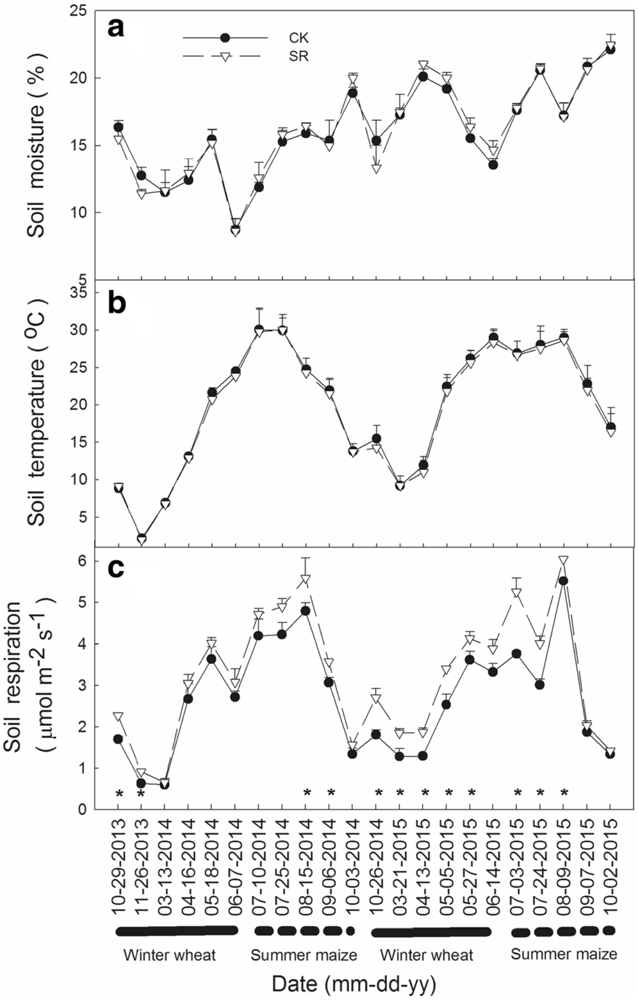

Fig. 1 Seasonal variations in soil moisture (**a**) and temperature (**b**) at 10 cm depth and soil respiration (**c**), error bars are standard deviations ($n = 3$). * are significantly different in soil respiration between CK and SR ($p < 0.05$). CK straw residues removal, SR straw residues application

3.2 Soil respiration responses to microclimate

Significant exponential relationship between soil respiration and temperature was found in both CK and SR ($p < 0.001$; Table S2, Electronic Supplementary Material). Soil temperature explained most of the seasonal variations (about 74%) of soil respiration. The Q_{10} values of CK and SR were 2.14 and 2.04 for the first wheat growing season, 1.88 and 1.84 for maize growing season, 1.73 and 1.51 for the second wheat growing season, and 2.08 and 2.28 for the second maize growing season. Correlation analysis showed poor relationship between soil respiration and moisture during 2013–2014 wheat growing season, but a significant and negative correlation between soil respiration and moisture was observed during 2014 maize, 2014–2015 wheat, and 2015 maize growing seasons (Fig. 2). Furthermore, a multiple regression including both soil temperature and moisture accounted for 70–72% of the seasonal variation in soil respiration (Table S3, Electronic Supplementary Material).

3.3 Effects of straw residues on soil chemical and biochemical properties

During 2013–2014 wheat growing season, NH_4^+-N concentration under the two treatments showed strong seasonal variations, which declined from wintering to tillering stage and was stable between tillering and jointing stages (Fig. 3a). It significantly decreased again at filling stage, and then became stable until maturity stage, but no significant difference was found between CK and SR at different stages. NO_3^--N concentration under CK increased from wintering to tillering stage and significantly decreased at jointing stage, but increased gradually until maturity stage (Fig. 3b). However, NO_3^--N concentration under SR did not change significantly during the whole growing season. Significant difference was observed between the two treatments only at tillering stage. EEG content under the two treatments increased gradually from wintering stage and reached maximum value at maturity stage. We found a significant and positive effect of straw application on EEG content during the whole growing season except jointing stage (Fig. 3c). During 2014 maize growing season, NH_4^+-N concentration under the two treatments showed similar seasonal patterns, which increased from seedling stage and reached peak at heading and filling stages but significantly decreased at maturity stage (Fig. 4a). NO_3^--N concentration under CK and SR also showed similar seasonal changes, which peaked at heading stage and significantly decreased at filling stage, and was stable until maturity stage (Fig. 4b). NH_4^+-N concentration under SR was significantly higher than CK at seedling stage and a significant difference between NO_3^--N concentration under SR and CK was observed at maturity stage (Fig. 4a, b). EEG content under CK gradually decreased from seedling stage to filling stage but

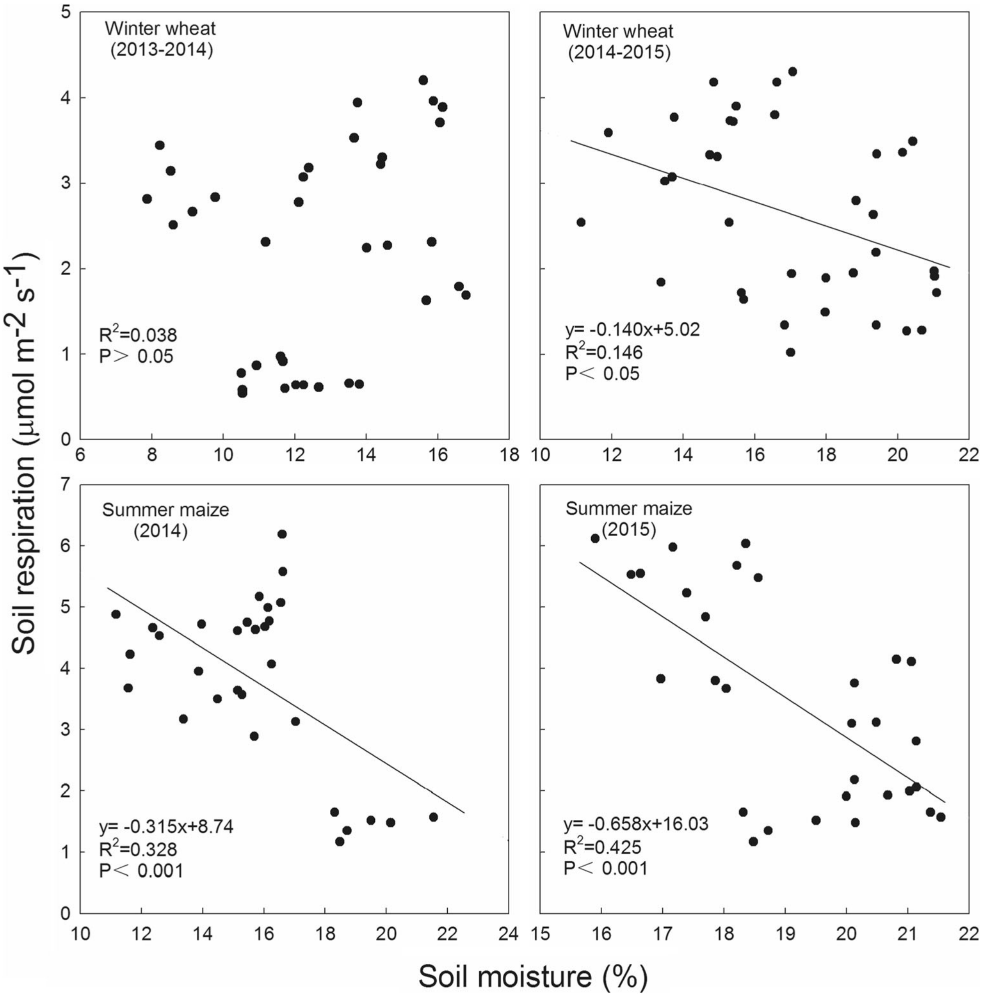

Fig. 2 Relationship between soil respiration and moisture during wheat and maize growing season

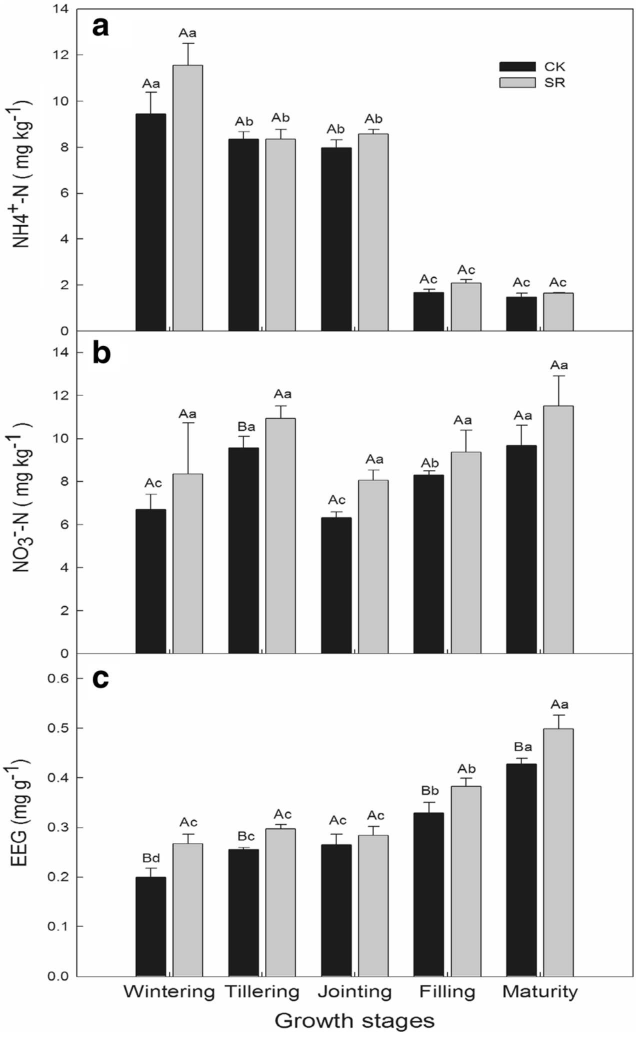

Fig. 3 Seasonal dynamics of ammonium N (NH_4^+-N) (**a**), nitrate N (NO_3^--N) contents (**b**), and EEG content (**c**) during 2013–2014 wheat growing season. Upper case letters show differences between CK and SR, lower case letters within stages ($P < 0.05$). CK straw residues removal, SR straw residues application, EEG easily extractable glomalin-related soil protein

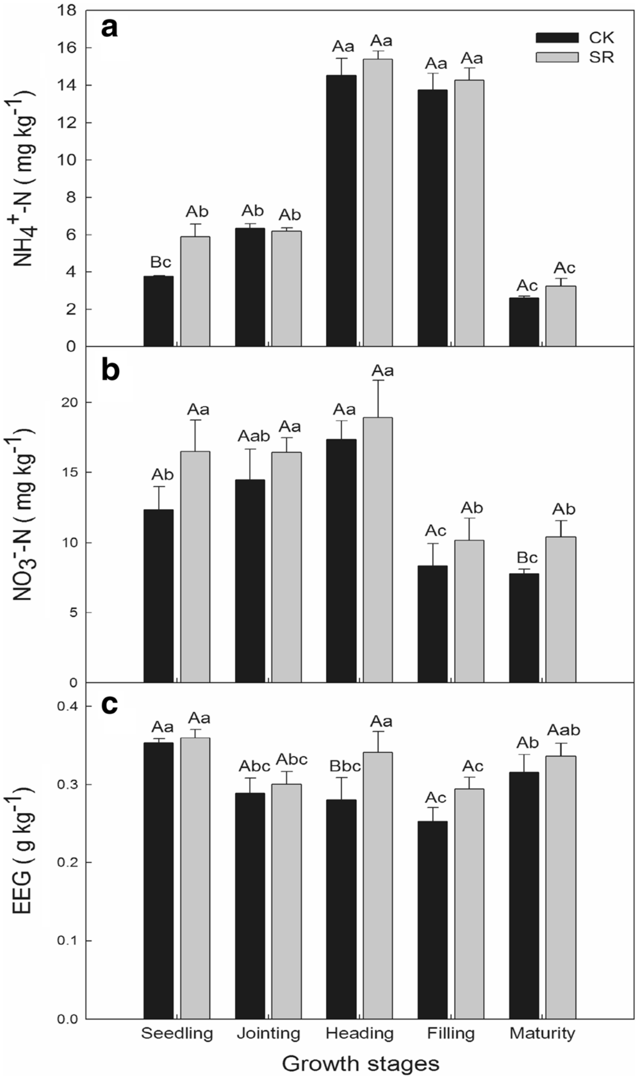

Fig. 4 Seasonal dynamics of ammonium N (NH_4^+-N) (**a**), nitrate N (NO_3^--N) contents (**b**), and EEG (**c**) during maize growing season (2014). Upper case letters show differences between CK and SR, lower case letters within stages ($P < 0.05$). CK straw residues removal; *SR* straw residues application; EEG easily extractable glomalin-related soil protein

increased at maturity stage (Fig. 4c). However, EEG content under SR showed frequent fluctuation trend. Significant difference between EEG content under SR and CK was found only at heading stage.

During 2013–2014 wheat growing season, BG activity under the two treatments exhibited similar changing trends, and straw application significantly stimulated BG activity at wintering, tillering, and filling stages (Fig. 5a). CBH activity under CK and SR reached minimum value at jointing stage, sharply increased and peaked at filling stage, but decreased again at maturity stage (Fig. 5b). CBH activity under SR was significantly higher than CK at wintering stage. During maize growing season, the activities of BG and CBH showed similar seasonal variations (Fig. 6a, b). Straw application did not significantly affect BG activity (Fig. 6a), but significant difference between CBH activity under CK and SR was found at seedling, heading, and filling stages (Fig. 6b).

SOC was not significantly influenced by straw residues (Table 1). Conversely, soil total N of SR was significantly higher than CK. Neither SOC nor soil total N under the two treatments significantly changed between the first and second wheat growing season.

Soil respiration was significantly and positively correlated with CBH ($P < 0.05$), EEG ($P < 0.05$), NH_4^+-N ($P < 0.05$) and NO_3^--N ($P < 0.05$) (Table 2). EEG also showed a significant positive correlation with NH_4^+-N ($P < 0.05$), BG ($P < 0.05$), and NO_3^--N ($P < 0.001$). In addition, BG showed a significant positive correlation at $p < 0.05$ level with NO_3^--N.

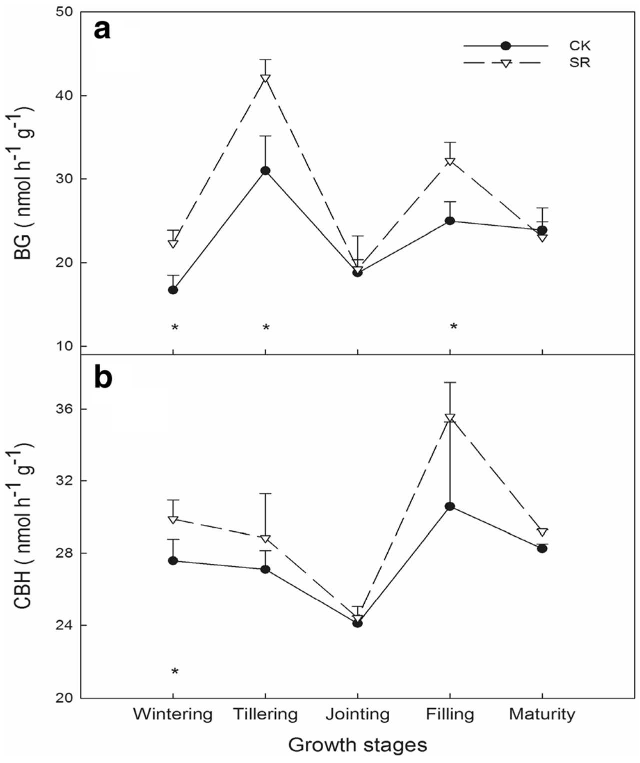

Fig. 5 Changes of BG (**a**) and CBH activities (**b**) during 2013–2014 wheat growing season. * are significantly different between CK and SR ($p < 0.05$). CK straw residues removal, SR straw residues application, BG β-glucosidase activity, CBH cellobiohydrolase activity

4 Discussion

4.1 Seasonal variations of soil respiration and driving factors

Many studies have found that soil temperature was the most important factor that affects the patterns of soil respiration (Iqbal et al. 2009; Huang et al. 2012). Wheat grew slowly during winter season because it was dormant, which meant crop did not need too much energy from autotrophic respiration. In addition, low temperature could inhibit microbial growth and resulted in the decrease of heterotrophic respiration. The marked decrease of both autotrophic and heterotrophic respiration led to the lowest value of soil respiration rate in winter season (November to January) at our study site (Fig. 1c). August to September was the period of high temperature in the whole year and also vigorous stage of maize. On the one hand, high temperature could stimulate microbial activity and then increase heterotrophic respiration. On the other hand, root biomass increased significantly to absorb nutrients in the soil for crop growth, which enhanced autotrophic respiration. Therefore, soil respiration rate was the highest during summer season (August to September) (Fig. 1c).

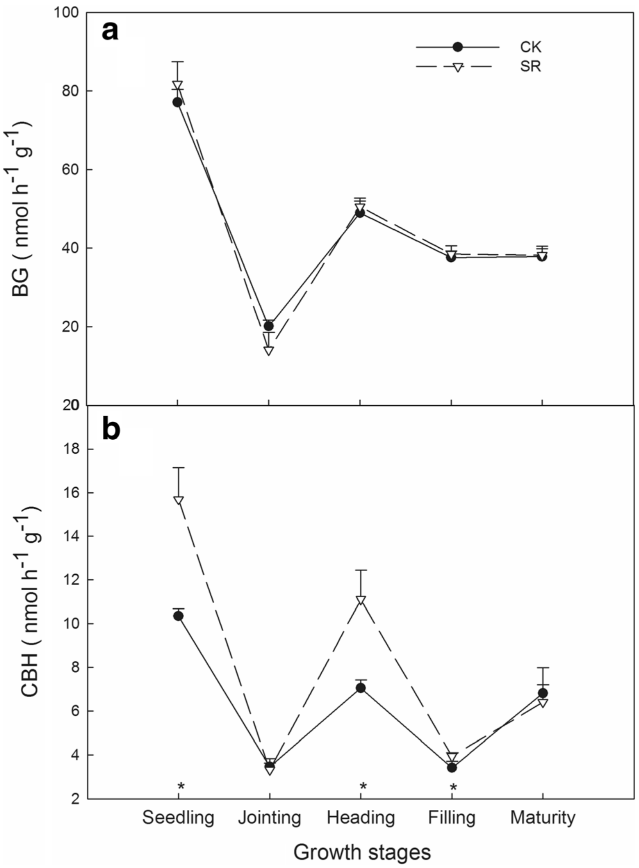

Fig. 6 Changes of BG (**a**) and CBH activities (**b**) during maize growing season (2014). * are significantly different between CK and SR ($p < 0.05$). CK straw residues removal, SR straw residues application, BG β-glucosidase activity, CBH cellobiohydrolase activity

Soil temperature and moisture were identified as the most important environmental factors influencing soil respiration in a wide range of ecosystems (Rey et al. 2011; Gong et al. 2014; Sun et al. 2014; Wang et al. 2014b). About 74% of the seasonal variations in soil respiration could be explained by soil temperature with an exponential equation under CK and SR treatments during wheat and maize growing season, which suggested that soil temperature was dominant factor influencing soil respiration at our study site. Previous studies showed that soil moisture had three different effects on respiration in agricultural ecosystem. Firstly, soil moisture did not significantly change soil respiration (Wang et al. 2014a). Secondly, soil respiration increased with the increase of soil water content because high soil moisture was beneficial to microbial and plant growth and then enhanced soil respiration (Li et al. 2013). Thirdly, Bowden et al. (2004) showed that soil respiration exhibited significant and negative correlation with soil moisture due to poor gas diffusion in surface soils and reduction in activity of obligate aerobic microbes caused by excessive water above the optimum soil moisture. In our study, during wheat-maize-wheat-maize growing season, mean

Table 1 SOC and total N at maturity stage during winter wheat growing season, the values are the means ($n = 3$) with SD

Treatments	SOC (g kg^{-1})		Total N (g kg^{-1})	
	Winter wheat (2014)	Winter wheat (2015)	Winter wheat (2014)	Winter wheat (2015)
CK	8.42 ± 0.21Aa	8.75 ± 0.05Aa	0.82 ± 0.02Ba	0.81 ± 0.01Ba
SR	8.61 ± 0.36Aa	9.02 ± 0.13Aa	0.93 ± 0.03Aa	0.93 ± 0.02Aa

Upper case letters show differences ($P < 0.05$) between CK and SR and lower case letters show differences ($P < 0.05$) between winter wheat in 2014 and 2015

CK straw residues removal, *SR* straw residues application

seasonal soil moisture was 12.6, 15.7, 17.0, and 19.1%, respectively (Fig. 2). Hence, the increase of mean seasonal soil moisture resulted in negative correlation between soil respiration and moisture, which showed that excessive soil moisture severely limits gas diffusion and then decreases soil respiration. The multiple regression model including both soil temperature and moisture could explain 70–72% of the seasonal variations in soil respiration, which was consistent with previous study (Li et al. 2013) and demonstrated that there was a significant interdependence between soil temperature and moisture in their effects on soil respiration at our study site.

4.2 The response of soil respiration to straw residues

As a common agricultural management that is widely used all over the world, straw application can affect soil respiration by altering soil properties. Even though many experiments have been done to detect the influence of straw application on soil respiration, limited numbers of studies explained the mechanism about the response of soil respiration to straw application at different growing stages. Apart from autotrophic respiration, another important source of soil respiration is heterotrophic respiration from soil microorganisms, which decompose organic residues and mineralize humus substances (Bond-Lamberty et al. 2004; Hanson et al. 2000). The significant and positive effect of straw residues on soil respiration during 2013–2014 (seedling and wintering stages) and 2014–2015 (seedling and tillering stages) wheat growing season and 2015 maize growing season (seedling stage) (Fig. 1c) might be explained as follows: (1) the presence of labile organic C from the decomposition of organic residues, easily utilized by soil organisms with release of CO_2 (Zavalloni et al. 2011), and (2) microorganisms were immediately stimulated to produce more soil enzymes related to C degradation after straw application. The significant increased activity of CBH with straw residues application (Figs. 5 and 6) and the positive correlation among CBH, EEG, and soil respiration (Table 2) showed that straw application may enhance heterotrophic respiration.

Table 2 Correlation matrix of soil respiration and soil biochemical parameters by using winter wheat growing season means during 2013–2015

	Rs	BG	CBH	EEG	NH_4^+-N
BG	NS				
CBH	0.855*	NS			
EEG	0.884*	0.865*	NS		
NH_4^+-N	0.895*	NS	NS	0.860*	
NO_3^--N	0.863*	0.888*	NS	0.996***	0.843*

Rs soil respiration, *BG* β-glucosidase activity, *CB* cellobiohydrolase activity, *EEG* easily extractable BRSPs, NH_4^+ *-N* ammonium N content, NO_3^- *-N* nitrate N content, *NS* not significant

$*P < 0.05$; $**P < 0.01$; $***P < 0.001$

A significant promotion effect of straw residues on soil respiration was also observed during 2014 (heading and filling stages) and 2015 (jointing and heading stages) maize growing season (Fig. 1c). The reason might be twofold: (1) Significant difference of CBH activity between CK and SR indicated that straw residues application could markedly increase heterotrophic respiration. (2) Hu et al. (2014) and Zhang et al. (2014) found that glomalin content was increased significantly by straw residues application, a positive correlation between soil respiration and glomalin content was also found in our results (Table 2). Therefore, straw application could improve microbial activity at vigorous growth period by increasing glomalin content which is a glycoprotein produced by AMF and then increase heterotrophic respiration.

4.3 Effects of straw residues on soil biochemical properties

Straw application is considered a good agricultural management because it can return crop straw into soil instead of CO_2 emission into atmosphere by burning method. Although many authors reported that straw residues addition improved significantly the level of SOC (Badia et al. 2013; Buysse et al. 2013; Mahmoodabadi and Heydarpour 2014), the absence of marked SOC difference between CK and SR was observed in our study. The reason might be that changes in SOC occur slowly and are relatively small compared to the vast background of SOC (Gong et al. 2009). Many previous studies (Lou et al. 2011; Choudhury et al. 2014; Wang et al. 2014a) also showed that SOC was not influenced significantly by straw residues after short-time experimental duration (< 5 years).

Since we have applied straw residues for 5 years (2010–2014), further studies are needed to detect if long-term straw application can significantly improve SOC at our study site.

Glomalin, which is produced by AMF, contributes to the preservation of organic carbon in the soil (Rilling et al. 2001). Straw residues might stimulate microbial growth by improving the microhabitat such as soil nutrient condition and porosity in which microbes lived, and then more glomalin was produced by microorganisms (Mikha and Rice 2004; Helgason et al. 2010). In our study, the application of straw residues significantly increased EEG content during wheat growing season, in agreement with the result of Zhang et al. (2014). This result demonstrated that straw residues should be applied at our study site because of its effect in improving glomalin content which is helpful for the preservation of organic carbon in the soil. Crop rotation was one of the farming practices that could significantly affect AMF. Boswell et al. (1998) found that a winter wheat cover crop could increase AMF colonization of maize in the following season. According to Ngosong et al. (2012), a larger impact was created by crop rotation on AMF than organic/inorganic fertilizer treatments. Therefore, the positive effect of crop rotation might offset the effect of straw application and then make the difference of EEG content between CK and SR treatment not significant at most growth stages in maize growing season. Since abundant nutrients was needed for maize growth at heading stage, the magnitude of the effect of straw application on AMF was bigger than that of crop rotation at this stage and then resulted in the only observed significant difference of EEG content between the two treatments at heading stage in maize growing season.

Soil enzymes, which are mainly secreted by soil microorganisms, can control the rate of soil nutrient cycling. Therefore, soil enzyme activities are the candidate “sensor” of soil management practice since they integrate information from microbial status and soil physicochemical conditions. BG and CBH were reported to be specific for the degradation of soil organic matter (Li et al. 2009; Stott et al. 2010). The meta-analysis study showed that water content could significantly stimulate BG activity but did not influence significantly CBH activity (Sinsabaugh et al. 2008). Mean seasonal soil moisture during 2013–2014 winter wheat and 2014 summer maize growing season was 12.6 and 15.7%, respectively. Soil moisture might become dominant factor that influences BG activity instead of straw application when water content increased. The increase of soil moisture might weaken the response of BG activity to straw application, which leads to no significant difference between BG activity of CK and SR treatment (Fig. 6). Straw residues induced the activities of BG and CBH at initial time, which was in agreement with previous studies (Chen et al. 2012; Dash et al. 2014; Tejada and Benitez 2014). This finding might result from the biodegradation of the organic matter added, which generated compounds that might act as substrates for the enzymatic activity (Benitez et al. 2005; Bastida et al. 2006). Straw residues also significantly increased the activities of BG and CBH at vigorous growth stages during wheat and maize growing season, because soil enzymes might be stimulated to decompose straw residues and then provided abundant nutrient for crop growth.

5 Conclusions

Soil respiration showed significant seasonal variation during wheat and maize growing season and was significantly increased by straw residues application at many growing stages. Straw application significantly increased EEG content during whole 2013–2014 wheat growing season except jointing stage. Moreover, application of straw residues had positive and significant effect on the activities of BG and CBH at initial and vigorous growth stages during wheat and maize growing season and resulted in the significant difference between CK and SR. Further research is needed to determine the impact of chronic straw application on soil respiration. Straw application is recommended as an agricultural management in the North China Plain because of its role in improving biochemical properties. Nevertheless, to improve soil biochemical parameters with a relative low soil respiration rate, further information is necessary about the optimum amount of straw application.

Acknowledgements This work was supported by the National Key Research and Development Program of China (2016YFD0300804), Special Fund for Agro-scientific Research in the Public Interest (201503120, 201203077, and 201203030), Science and Technology Project (2015BAD22B03), Fundamental Research Funds for Central Nonprofit Scientific Institution (1610132016035), and National 863 Program of China (2013AA102901).

Author contributions This work was carried out in collaboration between all authors. Author GL did experiment and wrote the first draft of the manuscript. Authors HW, DC, and XW designed the study. Authors HW, DC, and XW designed the study. Authors AAH, LG, BW, and SL measured soil respiration and detect some kinds of soil biochemical properties. Authors AAH and HW edited and reviewed the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no competing interests.

References

Ai C, Liang GQ, Sun JW, Wang XB, Zhou W (2012) Responses of extracellular enzyme activities and microbial community in both the rhizosphere and bulk soil to long-term fertilization practices in a fluvo-aquic soil. Geoderma 173-174:330–338

Allison SD, Czimczik CI, Treseder KK (2008) Microbial activity and soil respiration under nitrogen addition in Alaskan boreal forest. Glob Chang Biol 14:1156–1168

Allison SD, Wallenstein MD, Bradford MA (2010) Soil-carbon response to warming dependent on microbial physiology. Nat Geosci 3:336–340

Badia D, Marti C, Aguirre AJ (2013) Straw management effects on CO_2 efflux and C storage in different Mediterranean agricultural soils. Sci Total Environ 465:233–239

Bastida F, Moreno JL, Hernandez T, Garcia C (2006) Microbiological degradation index of soils in a semiarid climate. Soil Biol Biochem 38:3463–3473

Benitez E, Sainz H, Nogales R (2005) Hydrolytic enzyme activities of extracted humic substances during the vermicomposting of a lignocellulosic olive waste. Bioresour Technol 96:785–790

Bond-Lamberty B, Thomson A (2010) Temperature-associated increases in the global soil respiration record. Nature 464:579–582

Bond-Lamberty B, Wang CK, Gower ST (2004) A global relationship between the heterotrophic and autotrophic components of soil respiration? Glob Change Biol 10:1756–1766

Boswell EP, Koide RT, Shumway DL, Addy HD (1998) Winter wheat cover cropping, VA mycorrhizal fungi and maize growth and yield. Agric Ecosyst Environ 67:55–65

Bowden RD, Davidson E, Savage K, Arabia C, Steudler P (2004) Chronic nitrogen additions reduce total soil respiration and microbial respiration in temperate forest soils at the Harvard Forest. Forest Ecol Manag 196:43–56

Buysse P, Roisin C, Aubinet M (2013) Fifty years of contrasted residue management of an agricultural crop: impacts on the soil carbon budget and on soil heterotrophic respiration. Agric Ecosyst Environ 167:52–59

Chen XW, Post WM, Norby RJ, Classen AT (2011) Modeling soil respiration and variations in source components using a multi-factor global climate change experiment. Clim Chang 107:459–480

Chen RR, Blagodatskaya E, Senbayram M, Blagodatsky S, Myachina O, Dittert K, Kuzyakov Y (2012) Decomposition of biogas residues in soil and their effects on microbial growth kinetics and enzyme activities. Biomass Bioenergy 45:221–229

Chen L, Zhang JB, Zhao BZ, Zhou GX, Ruan L (2015) Bacterial community structure in maize stubble-amended soils with different moisture levels estimated by bar-coded pyrosequencing. Appl Soil Ecol 86:62–70

Choudhury SG, Sivastava S, Singh R, Chaudhari SK, Sharma DK, Singh SK, Sarkar D (2014) Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice-wheat cropping system under reclaimed sodic soil. Soil Till Res 136:76–83

Darenova E, Pavelka M, Acosta M (2014) Diurnal deviations in the relationship between CO_2 efflux and temperature: a case study. Catena 123:263–269

Dash PK, Roy KS, Neogi S, Nayak AK, Bhattacharyya P (2014) Gaseous carbon emission in relation to soil carbon fractions and microbial diversities as affected by organic amendments in tropical rice soil. Archives Agron Soil Sci 60:1345–1361

Davidson EA, Verchot LV, Cattanio JH, Ackerman IL, Carvalho JEM (2000) Effects of soil water content on soil respiration in forests and cattle pastures of eastern Amazonia. Biogeochemistry 48:53–69

Franzluebbers AJ, Hons FM, Zuberer DA (1995) Tillage-induced seasonal changes in soil physical properties affecting soil CO_2 evolution under intensive cropping. Soil Till Res 34:41–60

Gispert M, Emran M, Pardini G, Doni S, Ceccanti B (2013) The impact of land management and abandonment on soil enzymatic activity, glomalin content and aggregate stability. Geoderma 202-203:51–61

Gong W, Yan XY, Wang JY, Hu TX, Gong YB (2009) Long-term manure and fertilizer effects on soil organic matter fractions and microbes under a wheat-maize cropping system in northern China. Geoderma 149:318–324

Gong JR, Wang YH, Liu M, Huang YM, Yan X, Zhang ZY, Zhang W (2014) Effects of land use on soil respiration in the temperate steppe of Inner Mongolia, China. Soil Till Res 144:20–31

Hanson PJ, Edwards NT, Garten CT, Andrews JA (2000) Separating root and soil microbial contributions to soil respiration: a review of methods and observations. Biogeochemistry 48:115–146

Hashimoto S (2012) A new estimation of global soil greenhouse gas fluxes using a simple data-oriented model. PLoS One 7:e41962

Helgason BL, Walley FL, Germida JJ (2010) No-till soil management increases microbial biomass and alters community profiles in soil aggregates. Appl Soil Ecol 46:390–397

Hu WG, Jiao ZF, Wu FS, Liu YJ, Dong MX, Ma XJ, Fan TL, An LZ, Feng HY (2014) Long-term effects of fertilizer on soil enzymatic activity of wheat field soil in Loess Plateau, China. Ecotoxicology 23:2069–2080

Huang N, Niu Z, Zhan YL, Xu SG, Tappert MC, Wu CY, Huang WJ, Gao S, Hou XH, Cai DW (2012) Relationships between soil respiration and photosynthesis-related spectral vegetation indices in two cropland ecosystems. Agric For Meteorol 160:80–89

IPCC (2013) Climate change 2013: the physical science basis. Cambridge University Press, Cambridge

Iqbal J, Hu RG, Lin S, Hatano R, Feng ML, Lu L, Ahamadou B, Du LJ (2009) CO_2 emission in a subtropical red paddy soil (Ultisol) as affected by straw and N-fertilizer applications: a case study in southern China. Agric Ecosyst Environ 131:292–302

Khaliq A, Abbasi MK (2015) Improvements in the physical and chemical characteristics of degraded soils supplemented with organic-inorganic amendments in the Himalayan region of Kashmir, Pakistan. Catena 126:209–219

Li YT, Rouland C, Benedetti M, Li FB, Pando A, Lavelle P, Dai J (2009) Microbial biomass, enzyme and mineralization activity in relation to soil organic C, N and P turnover influenced by acid metal stress. Soil Biol Biochem 41:969–977

Li LJ, You MY, Shi HA, Ding XL, Qiao YF, Han XZ (2013) Soil CO_2 emissions from a cultivated Mollisol: effects of organic amendments, soil temperature, and moisture. Eur J Soil Biol 55:83–90

Liang GP, Houssou A, Wu HJ, Cai DX, Wu XP, Gao LL, Li J, Wang BS, Li SP (2015) Seasonal patterns of soil respiration and related soil biochemical properties under nitrogen addition in winter wheat field. PLoS One 10:e0144115

Lou YL, Xu MG, Wang W, Sun XL, Zhao K (2011) Return rate of straw residue affects soil organic C sequestration by chemical fertilization. Soil Till Res 113:70–73

Mahmoodabadi M, Heydarpour E (2014) Sequestration of organic carbon influenced by the application of straw residue and farmyard manure in two different soils. Int Agrophys 28:169–176

Meng L, Ding WX, Cai ZC (2005) Long-term application of organic manure and nitrogen fertilizer on N_2O emissions, soil quality and crop production in a sandy loam soil. Soil Biol Biochem 37:2037–2045

Mikha MM, Rice CW (2004) Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Sci Soc Am J 68:809–816

Ngosong C, Gabriel E, Ruess L (2012) Use of the signature fatty acid 16:1ω5 as a tool to determine the distribution of arbuscular mycorrhizal fungi in soil. J Lipids 2012:236807

Rey A, Pegoraro E, Oyonarte C, Were A, Escribano P, Raimundo J (2011) Impact of land degradation on soil respiration in a steppe (Stipa tenacissima L.) semi-arid ecosystem in the SE of Spain. Soil Biol Biochem 43:393–403

Rilling MC, Wright SF, Nichols KA, Schmidt WF, Torn MS (2001) Large contribution of arbuscular mycorrhizal fungi to soil carbon pools in tropical forest soils. Plant Soil 233:167–177

Rosier CL, Hoye AT, Rillig MC (2006) Glomalin-related soil protein: assessment of current detection and quantification tools. Soil Biol Biochem 38:2205–2211

Sinsabaugh RL, Lauber CL, Weintraub MN, Ahmed B, Allison SD, Crenshaw C, Contosta AR, Cusack D, Frey S, Gallo ME, Gartner TB, Hobbie SE, Holland K, Keeler BL, Powers JS, Stursova M, Takacs-Vesbach C, Waldrop MP, Wallenstein MD, Zak DR, Zeglin LH (2008) Stoichiometry of soil enzyme activity at global scale. Ecol Lett 11:1252–1264

Stott DE, Andrews SS, Liebig MA, Wienhold BJ, Karlen DL (2010) Evaluation of β-glucosidase activity as a soil quality indicator for the soil management assessment framework. Soil Sci Soc Am J 74: 107–119

Sun ZZ, Liu LL, Ma YC, Yin GD, Zhao C, Zhang Y, Piao SL (2014) The effect of nitrogen addition on soil respiration from a nitrogen-limited forest soil. Agric For Meteorol 197:103–110

Tejada M, Benitez C (2014) Effects of crushed maize straw residues on soil biological properties and soil restoration. Land Degrad Dev 25: 501–509

Thomas AD, Hoon SR (2010) Carbon dioxide fluxes from biologically-crusted Kalahari Sands after simulated wetting. J Arid Environ 74: 131–139

Wang ZL, Li YF, Chang SX, Zhang JJ, Jiang PK, Zhou GM, Shen ZM (2014a) Contrasting effects of bamboo leaf and its biochar on soil CO_2 efflux and labile organic carbon in an intensively managed Chinese chestnut plantation. Biol Fert Soils 50:1109–1119

Wang B, Zha TS, Jia X, Wu B, Zhang YQ, Qin SG (2014b) Soil moisture modifies the response of soil respiration to temperature in a desert shrub ecosystem. Biogeosciences 11:259–268

World Reference Base for Soil Resources (WRB) (2006) A framework for international classification, correlation and communication. Food and Agriculture Organization of the United Nations, Rome

Wright SF, Anderson RL (2000) Aggregate stability and glomalin in alternative crop rotations for the central Great Plains. Biol Fert Soils 31:249–253

Wu FS, Dong MX, Liu YJ, Ma XJ, An LZ, Young JPW, Feng HY (2011) Effects of long-term fertilization on AM fungal community structure and Glomalin-related soil protein in the Loess Plateau of China. Plant Soil 342:233–247

Zavalloni C, Alberti G, Biasiol S, Delle Vedove G, Fornasier F, Liu J, Peressotti A (2011) Microbial mineralization of biochar and wheat straw mixture in soil: a short-term study. Appl Soil Ecol 50:45–51

Zhang XK, Wu X, Zhang SX, Xing YH, Wang R, Liang WJ (2014) Organic amendment effects on aggregate-associated organic C, microbial biomass C and glomalin in agricultural soils. Catena 123: 188–194