RESEARCH ARTICLE

Soil respiration characteristics in different land uses and response of soil organic carbon to biochar addition in high-latitude agricultural area

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Abstract The farmland tillage practices changed the soil chemical properties, which also impacted the soil respiration (R_s) process and the soil carbon conservation. Originally, the farmland in northeast China had high soil carbon content, which was decreased in the recent decades due to the tillage practices. To better understand the R_s dynamics in different land use types and its relationship with soil carbon loss, soil samples at two layers (0–15 and 15–30 cm) were analyzed for organic carbon (OC), total nitrogen (TN), total phosphorus (TP), total carbon (TC), available nitrogen (AN), available phosphorus (AP), soil particle size distribution, as well as the R_s rate. The R_s rate of the paddy land was 0.22 (at 0–15 cm) and 3.01 (at 15–30 cm) times of the upland. The average concentrations of OC and clay content in cultivated areas were much lower than in non-cultivated areas. The partial least squares analysis suggested that the TC and TN were significantly related to the R_s process in cultivated soils. The upland soil was further used to test soil CO_2 emission response at different biochar addition levels during 70-days incubation. The measurement in the limited incubation period demonstrated that the addition of biochar improved the soil C content because it had high concentration of pyrogenic C, which was resistant to mineralization. The analysis showed that biochar addition can promote soil OC by mitigating carbon dioxide (CO_2) emission. The biochar addition achieved the best performance for the soil carbon conservation in high-latitude agricultural area due to the originally high carbon content.

Keywords Soil respiration · Land use · Biochar amendment · Soil organic carbon conservation · High-latitude agricultural area · Diffuse pollution

Introduction

The long-term tillage practices accelerate soil carbon loss by releasing CO_2 during the soil respiration (R_s) process (Greonigen et al. 2014), which has direct consequence on agriculture sustainable development and regional climate change (Abdalla et al. 2011). The R_s can affect the soil properties, especially for the soil with high concentration of organic carbon (OC) in Sanjiang Plain of northeast China. The soil OC concentration in this area decreased during the intensive agricultural reclamation over the past 30 years, and the soil conservation in the high-latitude area is more challenging due to the cold condition (Zhang 2010). The interactions between soil OC with R_s process and the efficiency of biochar addition for soil conservation have been studied (Smith et al. 2010; Suddick and Six 2013). However, the role of biochar was not fully understood in high-latitude agricultural area with high background soil OC concentration.

The R_s is the carbon release process from the soil as CO_2 (Rustad et al. 2000) and also the main chain in the terrestrial carbon cycle (Greonigen et al. 2014). At the global scale, about 98 Pg C is emitted to the atmosphere through R_s every year with an average annual growth of 2 to 7 % (Bond-Lamberty and Thomson 2010; Gong et al. 2014). The R_s rate is controlled by a range of factors, such as the soil hydrothermal condition and the land use conversion (Han et al. 2007; Almagro et al. 2013). The simple empirical temperature dependence equation (i.e. Q_{10}

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function) sometimes is amended by a scalar depending on water availability, which has been proved to predict R_s at global scale (Louis et al. 2014). However, it is still inadequate to characterize the interactions of R_s rate with other soil properties, such as fertility indictors (e.g., carbon, nitrogen, phosphorus concentration) and particle distribution (i.e., clay, silt, and sand content).

The land use conversions have been identified as the main contributor for greenhouse gas emissions during agricultural exploitation (Houghton et al. 1999; Campos 2006). The land use changes and crop rotations during the agricultural development directly impact the R_s rates due to the variance of soil temperature and erosion condition (Ouyang et al. 2010). Furthermore, the cultivation practices alter the soil physical, chemical, and biological properties, which are the important factors for the R_s process (Gamboa and Galicia 2011; Song et al. 2012). The knowledge of R_s response to land use changes is helpful in assessing human impacts on soil CO_2 emission, but little information is available in high-latitude area (Chen et al. 1995).

The biochar is the solid carbonaceous product of the slow pyrolysis (heating in the absence of oxygen) and with high carbon content, which can improve soil quality and increase soil carbon sequestration (Lehmann et al. 2006). The biochar is applied as soil amendments can affect the soil pH and increase soil cation exchange capacity (Mukherjee et al. 2014). These responses reversely affect the soil CO_2 emission and also improve the nutrients circle (Spokas and Reicosky 2009). The addition of biochar to the farmland can increase soil organic matter content and improve soil fertility (Moon et al. 2013). The agricultural soils with biochar amendment can sustain fertility, which has gained increasing attentions and has led to a surge in soil and environmental protection (Arthur et al. 2015).

To mitigate the soil CO_2 emission and conserve soil carbon with biochar, it is hypothesized that the R_s dynamics existed in different land use types and is sensitive to the different loads of biochar addition. The biochar addition threshold value and the interaction with soil OC in high-latitude agricultural area is still not clear. In this study, the soil R_s rate at two depths were analyzed in four representative types of land uses, and the impact of biochar addition was also identified for the upland soils. The specific objectives of this study were (a) to examine the R_s rate variations in four dominant types of land uses in high-latitude agricultural area, (b) to identify the relationship between soil chemical parameters with R_s rate, and (c) to assess the best performance of the biochar additions for soil OC conservation and CO_2 emission mitigation in upland.

Materials and methods

Study area description

The case study area in northeast China has a total area of 142.5 km^2 and represents the typical rural landscape in high-

latitude area. This area was historically covered mainly with wetland and forest, but it has been undergoing an intensive land reclamation since 1970s (Jiao et al. 2014). The land use conversions over the natural land covers and intensive tillage practice decreased the farmland soil OC concentration, which also affected the soil fertility and the transport of other elements. The climate of this high-latitude agricultural area is continental monsoon, with the average annual rainfall and air temperature of 600 mm and 3 °C, respectively (Ouyang et al. 2013) (Fig. 1).

Soil collection and preparation

The total of 39 soil sample sites, including 13 from upland, 11 from paddy land, 9 from forest, and 6 from wetland, were selected in July 2013. These four types of land use are the dominant in this area, and the previous studies have shown that land use change mainly impacts the soil properties and reserves at top 40 cm layer (Jobbagy and Jackson 2000). Considering the local soil structure and the tillage depth, three sub-samples at two depths (0–15 and 15–30 cm) were obtained and fully mixed as a composite sample for each sampling site. After transported to the laboratory, the soil samples were air dried at room temperature, ground through a 2-mm nylon sieve, and stored in plastic bags for soil physicochemical analysis.

In order to analyze the R_s rate in each site, another three undisturbed soil samples on the same sites of previous samplings were also collected at 0–15 and 15–30 cm by a circular stainless tube of 100 cm^3, which was used for the R_s measurement. The soil samples were stored under 4 °C and transported to laboratory as soon as possible after collection.

Soil respiration rate analysis

The Barometric Process Separation (BaPS) System (UMS GmbH, Germany) was applied to obtain the R_s rate difference of two depths in the four kinds of land use. The BaPS is based on the determination of the CO_2, O_2, and total gas balances inside an isothermal, gas-tight soil system. The R_s is the main biological process and was measured by the gas pressure changes inside such a system. The soil samples for R_s analysis were undisturbed soil columns of 100 cm^3. The inputs, namely the soil sample weight and pH values of the each experimental group, were measured three times. The system temperature was set as the real-time temperature of soils and kept constantly during the experiments using water bath. The R_s rate can be precisely evaluated by testing temperature, air pressure change, and gas dissolutions in the system.

Soil physicochemical properties analysis

The R_s of four types of land use showed that the R_s in two types of farmlands were active. In order to distinguish the
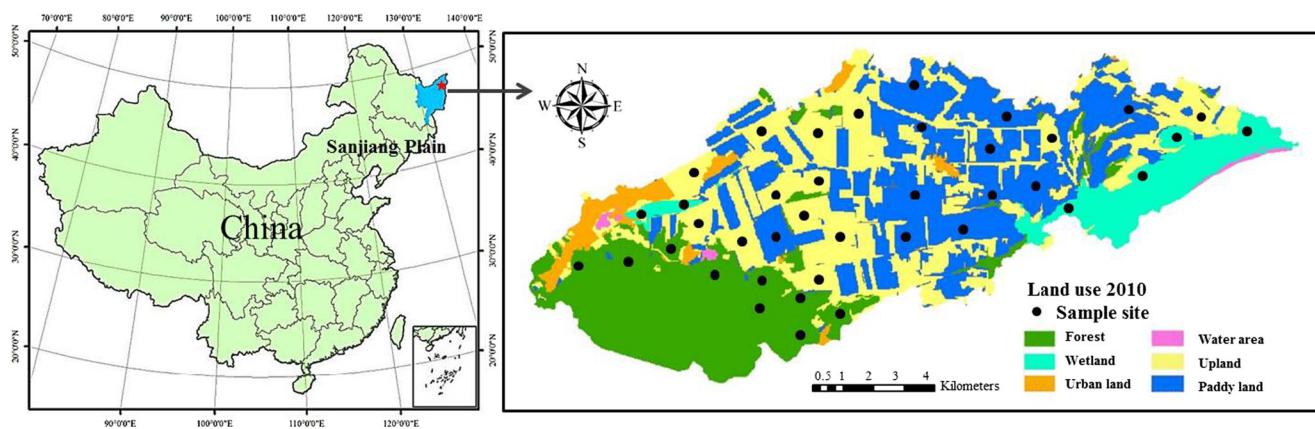
Fig. 1 Location of study area showing land uses and sampling sites

interactions between R_s with the soil properties, nine soil parameters of the farmland soils at two depths from four kinds of land uses were analyzed. The soil particle size distribution was determined by a laser particle size analyzer (SEDIMAT 4–12, Germany). The total carbon (TC) and nitrogen (TN) were measured with a C/H/N Elemental Analyzer (Euro Vector S.P.A EA3000, Milan, Italy). The available nitrogen (AN) was determined by the NaOH diffusion method (Stanford 1982). The soil organic matter was measured by concentrated sulfuric acid, potassium dichromate method, which was converted to organic carbon (OC) according to the Van Bemmelen factor of 1.724 (Blevins et al. 1977). The total phosphorus (TP) was determined by the inductively coupled plasma-atomic emission spectrometry after acid digestion (ICP-OES, SPECTRO ARCOS EOP, Analytical Instruments GmbH, Germany). The available phosphorus (AP) was extracted with 0.5 M NaHCO$_3$, diluted fivefold with distilled water (Olson et al. 1954), and then determined by ICP-OES. The soil pH was measured using a pH meter with a soil water ratio of 1:5 (Delta 320, Mettler-Toledo, Greifensee, Switzerland).

Biochar incubation scheme

To better assess the response of R_s process and soil OC dynamics to the biochar addition, the upland soil was employed for the incubation experiments and without the impacts of the varied soil water conditions. The laboratory incubation experiments measured the soil CO$_2$ emission at different levels of biochar addition. The biochar was a solid carbonaceous product of pyrolyzed corn straw at 450 °C, which had a high carbon content of 70.5 % and an ash content of 9.03 % (Zhao et al. 2013). The incubation experiments were set up with three levels of biochar addition with three replicates (Table 1). The soil without biochar addition was set as the control (CK). The 50-g soil was treated with distilled water to achieve the desired water content (30 %) and added to an Erlenmeyer flask (500 ml). Then, pre-incubation were

developed at 20 °C for 7 days. For the samples with three kinds of addition (C1, C2, and C3), the biochar was evenly added on the eighth day and then the incubation started. The headspace air was sampled on the 1st, 3rd, 6th, 9th, 14th, 20th, 26th, 32th, 39th, 46th, 53rd, 60th, and 70th days of the incubation by a gas-tight syringe. The 70-day incubation period presented the begging and the stable stages of the soil amendment, which provided the necessary information of the response analysis. Before gas sampling, the headspace air in the flasks were thoroughly flushed with ambient air for 15 min. Then, the flask was capped immediately by sealing with rubber stopper for 2 h. The flasks were flushed with ambient air again after sampling and kept with sealing membrane. The CO$_2$ emission was detected by a gas chromatograph (Agilent 7890A, USA).

Statistical analysis

The R_s dynamics at two depths of four kinds of land use were analyzed with the one-way analysis of variance (ANOVA). Before running ANOVAs, all the data sets were checked for the normality by using One-Sample Kolmogorov-Smirnov test. After identifying that the paddy land and the upland had higher R_s rate than the natural land covers, their soil properties' interaction with R_s were analyzed. The statistical method partial least squares (PLS) regression analysis was performed to assess the relationships between R_s rates and selected physicochemical properties in farmlands (Conforti et al. 2015). The relationship assessment standard of PLS was to plot the

Table 1 Treatments for the biochar incubation experiment

Abbreviation	Treatment
CK	Soil without biochar addition
C1	50 g Soil with 0.07 % (w/w) biochar addition
C2	50 g Soil with 0.14 % (w/w) biochar addition
C3	50 g Soil with 0.21 % (w/w) biochar addition

w*'s and c's of one regression dimension against another, which can assess the relationships of R_s with multiple parameters at the same time (Simfukwe et al. 2011). The R_s rate was chosen as the dependent variable Y and nine soil physicochemical parameters were considered as the independent variable X, which presented the information of the dominant factor. The spatial distributions of PLS analysis about two kinds of farmlands demonstrated the relationship difference by direct comparison.

Results

Soil properties of different land uses

The regional farmland was converted from the original natural land covers, and the soil physicochemical properties at two depths among the land uses were analyzed (Table 2). The wetland had the highest TC and OC concentrations at 15–30 cm, which were significantly higher than those in the upland and paddy land. The wetland also had the lowest concentrations of TN and AN, with the averages of 0.99 g kg^{-1} and 50.61 mg kg^{-1}, respectively. The silt content also did not present significant difference, but the sand content was significantly different among the land uses. The biggest sand content was the 32.92 % in the upland, and the smallest one was the 22.16 % in wetland.

The TC, TN, OC concentrations and clay content in wetland were much higher than in cultivated lands at 0–15 cm, but they did not significantly differ with the forest. The TP concentration in paddy land was the lowest (0.89 g kg^{-1}), which was approximately 63 % of the value in forest (1.41 g kg^{-1}). The AN and AP concentrations in the four types of land uses varied from 92.93 to 106.58 and 9.78 to 10.45 mg kg^{-1} respectively, but no significant difference was found among them. The AP concentration in upland was 9.51 mg kg^{-1}, much bigger than the value of

8.38 mg kg^{-1} in paddy land. There was no significant difference in TP concentration as well as soil particle size distribution among the four types of land uses. The lower OC concentration and clay content in the upland and paddy land were the direct consequence of tillage practice and also the main characteristics in this high-latitude agricultural area.

R_s difference in four types of land uses

The R_s difference in dominant four types of land use in this high-latitude agricultural area was compared (Fig. 2). The R_s rate in paddy land was the highest, and the wetlands had the lowest value based on the averaged value. The vertical pattern R_s rates of four types of land uses were compared. The R_s rates varied from 380.06 to 513.74 µgC kg^{-1} SDW h^{-1} at 0–15 cm. The forest and upland had similar R_s rates, which were 474.12 and 420.54 µgC kg^{-1} SDW h^{-1}, respectively. The paddy land had the highest R_s rate of 602.19 µgC kg^{-1} SDW h^{-1} at 15–30 cm, but the upland had the smallest value (150.13 µgC kg^{-1} SDW h^{-1}) at this depth. The R_s rate at the deeper layer of forest and wetland was 330.36 µgC kg^{-1} SDW h^{-1} and 252.53 µgC kg^{-1} SDW h^{-1}, respectively. Except the paddy land, the R_s rate of other three types of land uses decreased in the vertical direction. The average R_s rate at 0–15 cm was 452.96 µgC kg^{-1} SDW h^{-1}, which was bigger than the 334.98 µgC kg^{-1} SDW h^{-1} at 15–30 cm. Therefore, the conversion of natural land cover to upland did not improve the R_s rate intensively, but the expanding area of paddy rice increased the regional R_s rate.

Interactions of soil properties with R_s rate in farmlands

As the soil properties of two kinds of farmlands suffered huge impacts and their R_s rates were also differed with other two kinds of natural land covers, the interactions between them were evaluated with the partial least squares regression analysis. The higher R_s rate in paddy land caused the different

Table 2 Soil properties at 0–15 and 15–30 cm of four types of land uses

Depth (cm)	Land use	TC (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	OC (g kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	Clay (%)	Silt (%)	Sand (%)
0–15	Forest	36.47ab	3.19a	1.41a	33.49a	96.34a	9.78a	33.37a	40.75a	25.88ac
	Wetland	46.05b	3.88a	0.91b	36.36a	98.52a	10.45a	36.74a	41.10a	22.16a
	Upland	30.69a	1.91b	1.31a	26.05b	106.58a	10.16a	24.13b	42.95a	32.92b
	Paddy land	26.67a	1.67b	0.90b	18.85c	92.93a	10.05a	27.90c	43.16a	28.94c
	Mean	34.96	2.66	1.13	28.69	98.59	10.11	29.27	42.21	28.52
15–30	Forest	32.53a	2.38a	1.03a	22.21a	72.57a	9.03ab	35.41a	33.14a	31.45a
	Wetland	39.21a	0.99b	0.89a	31.58b	50.61b	9.39a	37.18a	34.11a	28.71a
	Upland	23.39b	1.86c	0.92a	20.24ac	88.37c	9.51a	36.40a	34.19a	29.41a
	Paddy land	19.32b	1.41d	0.88a	16.04c	74.58ac	8.38b	36.27a	33.70a	30.03a
	Mean	28.61	1.66	0.93	22.52	71.53	9.08	36.26	33.80	29.95

For each depth, the different letters (a, b, c, d) represent significant differences ($P<0.05$)
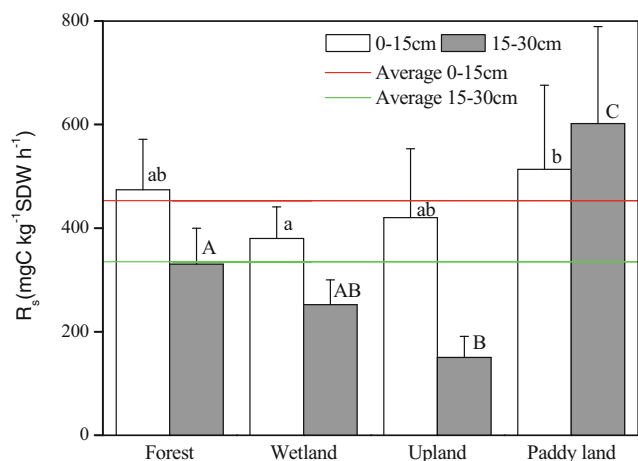
Fig. 2 The R_s rates (mean±S.D.) at two depths of four types of land uses. The different lower case letters (*a*, *b*, *c*) represent significant differences ($P<0.05$) at 0–15 cm, the different uppercase letter (*A*, *B*, *C*) represent significant differences ($P<0.05$) at 15–30 cm

distributions of the parameters. The TN and AN were the first two important contributors for the R_s rate dynamics at 0–15 cm in upland (Fig. 3a). Their R^2 value reached 1.552 and 1.343, respectively, which were the biggest value among all the evaluated indexes. The AP and TP in paddy land were negatively correlated with the R_s process, and the interaction value were 2.008 and 1.206, respectively ($R^2>1.00$, Fig. 3b). The nitrogen had more chance to transport in the higher water content condition in paddy land, which lowered down the impact of nitrogen on R_s.

The PLS analysis demonstrated that the TC, TN, OC concentrations and clay content were still the major factors for R_s rate at 0–15 cm soils of paddy land. This was the special characteristics in the area due to the higher soil OC background concentration. It was also found that the interactions between soil properties and R_s rate varied in vertical direction. The TC, TN concentrations and the clay content showed positive relationships with the R_s rate at 15–30 cm, which meant

that the R_s rate reduction was related to the losses of TC and clay content in deeper soil of upland.

Soil CO$_2$ emission and carbon residue at different levels of biochar addition

After identifying that the farmland soil OC and R_s rate experienced the significant impact during the long-term tillage and presented close correlations, the upland soil was selected for the biochar addition experiments. The direct reason for the selection was to neglect the impact of soil water and highlight the impact of biochar addition. As the limited experimental conditions, the incubation period of biochar addition was set 70 days. The CO$_2$ emission rate from upland soil incubated with different levels of biochar were monitored (Fig. 4). The CO$_2$ emission varied significantly in the temporal direction, but observed similar trends among four treatments during the incubation period. This meant that the transformation mechanism of carbon after the incubation at different levels was similar. The CO$_2$ emission rate was higher in the early 10 days after the biochar addition, which fluctuated and then dropped to the stable low rate. The CO$_2$ emission rate in the CK without biochar addition was bigger than the other three scenarios in the middle of incubation period, but was slightly smaller in the early and later period. This difference meant that the addition of biochar depressed the CO$_2$ emission. About three biochar addition scenarios, the soils with the highest biochar addition (C3) emitted more CO$_2$ than the C1 and C2. The emitted CO$_2$ gradually reduced and kept at a minimum rate after the 46th day, which meant the 70-day monitoring covered the active soil response period.

The cumulative CO$_2$ emission by R_s process under four addition scenarios during the 70-day incubation period were summarized in Fig. 5. The cumulative emissions of CO$_2$ of four experiments lined in the order of CK>C3>C1>C2. The CO$_2$ discharge difference become bigger after the 30 days,
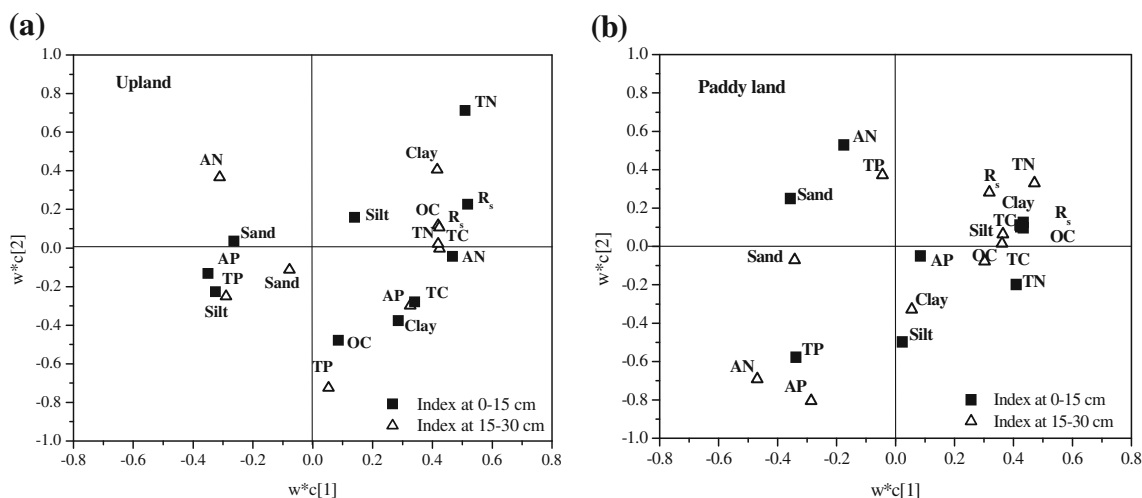

Fig. 3 Weight plot of the first two PLS components for R_s rate with soil properties at two depths of farmlands
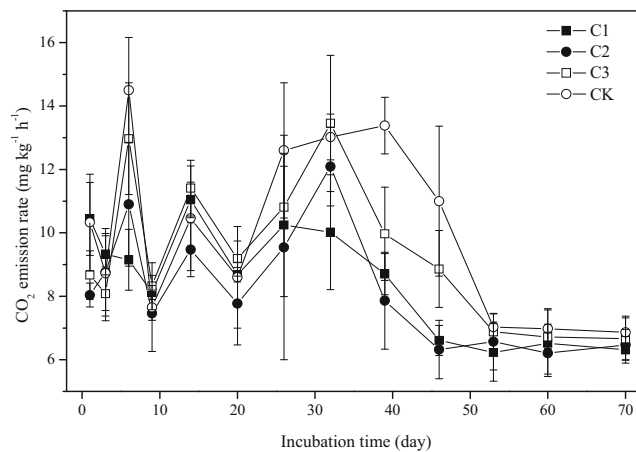
Fig. 4 Dynamics of CO_2 emission rate in soils with diverse biochar addition levels during the incubation period

which meant the interaction between the biochar with CO_2 production was mainly relied on the slow biological R_s process. On the other hand, the bigger gap in the later period meant that the biochar addition affected the carbon circle after adapted to the soil environment. However, the difference between C1 and C2 was kept at the smaller gap, which meant that the addition load difference between C1 and C2 was not so obvious. The response difference of CO_2 emission to the biochar addition also demonstrated that there was a threshold value for the additional load.

The soil carbon concentration experienced a 14.70 % decrease down to 26.2 g kg^{-1} after the 70 days incubation period in CK, which was the biggest loss of four scenarios. The C1 addition load was the smallest one, and the soil TC concentration had the obvious increase than the CK. After the 11.96 % decrease in C1, the soil TC was 27.5 g kg^{-1}. The C3 and C4 had the bigger carbon addition load, and the soil TC decreased 11.54 and 13.05 % respectively. The experiments showed the lower and higher carbon additions both

accelerated the R_s process and intensified the CO_2 emission. From the aspect of soil carbon improvement, the C1 addition got the maximum carbon residue percentage in soil.

Discussion

The R_s dynamics with soil properties

The R_s as a soil biological process is the soil carbon circle with the interactions of other elements. The R_s process is mainly affected by the soil properties and soil environment, which also change the soil properties reversely (Jones et al. 2011). The PLS analysis showed the vertical interactions variance between soil property with R_s in two kinds of farmlands (Fig. 3). The soil nitrogen and OC are the direct triggers for soil CO_2 emission, which have close interaction with R_s rate in the natural land as well as the farmland. As TN correlated well with R_s rate at both layers of upland, the nitrogen fertilization application during the tillage practice is the potential factor to adjust R_s rate. The AP also provide some evidences to assess R_s rate in deeper paddy land, because it is often tightly bound to soil particles and easily accumulated in the irrigated soil (Withers and Hodgkinson 2009). On the contrary, the AN and AP are soluble elements and easily influenced by slope surface runoff in the paddy land. Therefore, some amounts of these elements dissolve in surface water and lost by runoff of the paddy land, which make their interactions with R_s weaker than in upland soils.

About the soil mechanical composition, it is noted that the clay content is the reliable index for soil R_s and OC dynamics (Pawlett et al. 2013). The paddy land is more easily affected by soil erosion, which tends to be selective toward fine particles (Jiao et al. 2014). Under the fewer clay content, more sand content, the repeated irrigation and nutrients addition intensify
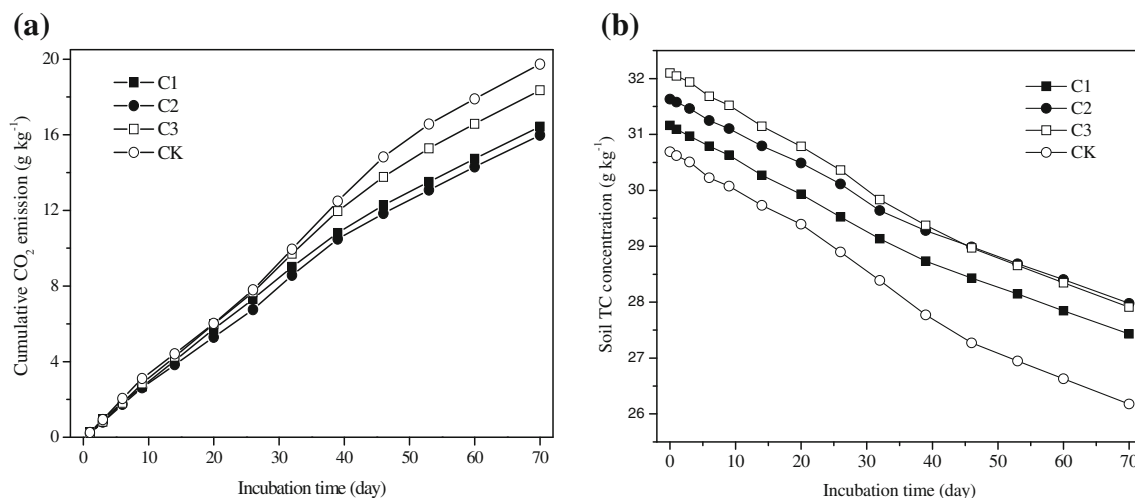

Fig. 5 The cumulative CO_2 emission and soil TC variation during incubation period

the R_s process in the paddy land. On the other hand, the intensive R_s process increases the discharge of soil carbon, which reversely decreases the soil clay content. Thereafter, the clay content showed in the upland has stronger relation with R_s than in the paddy land. The interaction analysis helps to predict the consequence of R_s on soil clay and sand content.

The R_s difference among land use in high-latitude area

The local land use conversions and the subsequent cultivation practices in farmlands directly affected soil properties (Table 2), which is similar as other agricultural development area (Foley et al. 2005). The paddy land in this high-latitude area showed much higher R_s rate at two depths than the other natural land covers (Fig. 2), which indicate the reclamations of farmland cause more CO_2 release from the soils. With the comparison of R_s rate at two depths of four types of land uses, the vertical differences of the interactions of soil properties with R_s rate were also identified (Fig. 3). The higher R_s rate of the topsoil in farmland means that it is sensitive to the tillage practice (Huang et al. 2014). The R_s rate at 15–30 cm depth of paddy land was bigger than the other three types land uses (Fig. 2), probably because the rice cultivation in paddy field has cyclical irrigations and nutrients addition. The higher R_s rate in paddy land than the upland under the similar cultivation impacts meant the higher soil water content affect the R_s process (Kasimir-Klemedtsson et al. 2007; Reicosly and Archer 2007). The higher R_s in paddy land than the wetlands also mean that the water content is not the only critical factor. The combined impacts of soil water and nutrient addition are the direct reason for higher R_s rate in paddy land.

The tillage practice can disrupt farmland soil aggregates, improve soil aeration, and expose fresh organic matter in soils to microbial decomposition, which promote the gas exchange with atmosphere (Six et al. 2004; Dieckow et al. 2009). The higher background soil OC concentration and intensive tillage improve the R_s rate in this high-latitude agricultural area at same time. The soil particle distribution is also the regular indicator for this anthropogenic impact on R_s process (Dilustro et al. 2005). In this study, the clay content was found strongly interacted with surface R_s rate in paddy land and subsurface R_s rate in upland. The strong correlations demonstrate that the continuous clay loss and sand increase will cause more aerated soil condition and accelerate the R_s rate (Oral et al. 2013). Therefore, the soil OC and clay loss will be more serious if there is no soil carbon amendment in this agricultural area.

Implications of biochar for SOC amendment

The CO_2 emission is an important way for soil OC loss, and the high soil OC concentration is a direct carbon contributor for R_s (Marinozzi et al. 2011). Under the influence of the intensive tillage practices, the soil TC concentrations in the upland and paddy land were both lower than the regional averaged value and the concentration of natural land covers (Table 1). The background soil TC level (26–46 g kg^{-1}) in this high-latitude area is higher than the other regular farmland in warm or tropical area. Under the limited incubation period, the biochar amendment is proved to efficiently promote soil OC conservation and diminish CO_2 emission. Compared to the similar analysis in the farmland soil without high soil OC concentration (Zavalloni et al. 2011), the R_s rate in this high-latitude agricultural area is higher and the threshold value of biochar addition is lower. As the background soil OC in upland was about 33 g kg^{-1}, the maximum carbon increased in soil after biochar addition is not appeared in the biggest addition (Fig. 5). The performance of the biochar is the combined consequences of the original soil OC concentration and soil water content. The biochar addition can disconnect the relationship between clay content with R_s, which will depress the CO_2 emission and improve the soil OC concentration.

The tillage practice adjustment is also the potential option for regional soil carbon protection. The conservation tillage such as corn-soybean rotation can enhance the retention of SOC and consistently reduces soil CO_2 emission compared with conventional tillage (Abdalla et al. 2013). Furthermore, necessary tillage management intervention in combination with crops rotation can modify soil water-holding capacity (Drury et al. 2006), especially in such cool and humid region. This will finally provide more capacity to reduce agricultural soil CO_2 emission, which is a key factor for global warming and needs to be controlled (Ouyang et al. 2014).

Conclusion

The findings demonstrated the R_s rate dynamics differences among land uses as well as soil depth. The R_s rate was much higher in paddy land than in other land uses, especially the average R_s rate at 15–30-cm depth was 3.01 times higher than upland. The PLS analysis demonstrated that the interactions of soil properties and R_s rate varied between the paddy land and upland. The cycling irrigations and nutrient addition intensified the R_s process and decreased the content of clay. The soil TC and TN concentration were identified as the most significant chemical indexes for the R_s process in cultivated soil. The soil clay content also provided more reliable information to indicate the R_s rate variation in topsoil. The farmland had higher R_s rate than the natural land covers, which decreased the clay content and the soil fertility level. Reversely, the smaller clay content caused the higher R_s rate. So, the biochar addition was used to disconnect these chains.

The CO_2 emission rate monitoring over biochar incubation 70 days meant it reached the stable stages, and the analysis demonstrated that the artificial source of carbon can depress

the R_s rate. From the aspect of soil carbon optimization, the 50 g soil with 0.07 % (w/w) biochar addition led to the maximum carbon residue percentage in soil. The farmland soil in the high-latitude area with plenty of OC presented the higher speed of carbon sequestration and CO_2 emissions with the other warm or tropical agricultural areas, so the threshold value of biochar addition was also lower. The long-term on-site biochar incubation monitoring in this high-latitude agricultural area will provide more detailed information.

Conflict of interest The samplings of the soil were permitted by the local farm. Information obtained from other publication has been cited properly. All contributors to this paper have been listed in the authors and all the authors had read the final version and agreed to the submission. All authors declare that they have no competing interests.

Human and animal rights and informed consent The research did not involve the human participants and animals. The supporters of the study have been clearly listed in the MS.

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