Science of the Total Environment 569–570 (2016) 390–394

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Temperature and moisture responses to carbon mineralization in the biochar-amended saline soil

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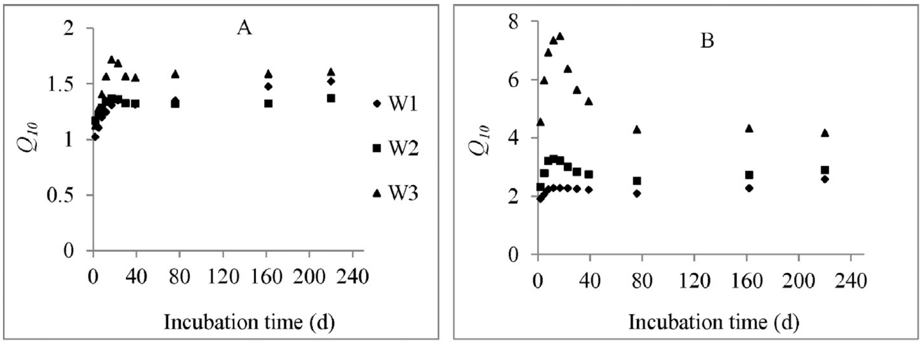
HIGHLIGHTS

- Cumulative C_{min} increases with biochar added and incubation temperature.
- The temperature rise reduced the turnover time of C pools and Q_{10}.
- Cumulative C_{min} follows different trends under varying moisture conditions.
- The two-compartment model could well describe the dynamics of C_{min}.

GRAPHICAL ABSTRACT



Temperature sensitivity (Q_{10}) of carbon mineralization in saline soil under different incubation conditions (15–35°C)

ARTICLE INFO

Article history:
Received 2 May 2016
Received in revised form 12 June 2016
Accepted 13 June 2016
Available online xxxx

Keywords:
Carbon mineralization
Biochar
Temperature
Soil moisture
Saline soil

ABSTRACT

This study assessed the effects of temperature and moisture on carbon mineralization (C_{min}) in a saline soil system with biochar amendment. The dynamics of C_{min} were monitored in a biochar-amended saline soil for 220 days by incubation experiments under different conditions of temperature (15 °C, 25 °C and 35 °C) and moisture (30%, 70% and 105% of the water-holding capacity). Results showed that as the incubation temperature rose, cumulative C_{min} consistently increased in soil added with 0–4% biochar. The two-compartment model could well describe the dynamics of C_{min}. The temperature rise increased the concentration of labile C in soil, but reduced the turnover time of labile and recalcitrant C pools and the value of temperature coefficient Q_{10}. The response of C_{min} to moisture was varying in soil amended with different levels of biochar. In the control treatment (soil alone), cumulative C_{min} increased only when soil moisture was >105%. In the biochar treatments, however, 70% of water-holding capacity was optimal for C_{min}, except for 2%-biochar treatment at 35 °C. The findings highlight the necessity to consider the combined effects of soil moisture, temperature and the amount of biochar added for assessing C_{min} in biochar-amended saline soils.

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http://dx.doi.org/10.1016/j.scitotenv.2016.06.082
0048-9697/

1. Introduction

Soil hardening, low permeability, and poor water retention–fertilizer conservation capacity are serious issues limiting soil production potential in coastal saline soils of the Yellow River Delta (Wang et al., 2010). Biochar is a solid pyrolysis product of biological matter under anoxic or hypoxic conditions at high temperatures. It typically contains 40–75% carbon (C), characterized by porous structure, large surface area, and high ion exchange capacity (Lehmann and Joseph, 2009). Application of biochar to saline soils will help to improve soil nutrient content (de la Rosa et al., 2014; Tian et al., 2016), enhance water retention–fertilizer conservation capacity (Gray et al., 2014; El-Naggar et al., 2015; Bass et al., 2016), and promote crop growth (Lashari et al., 2013; Liu et al., 2014; Agegnehu et al., 2016).

Despite its benefits mentioned above, biochar amendment may break the existing soil C balance and affect the assessment and prediction of C cycle in the soil ecosystem (Bolan et al., 2012; Bruun et al., 2011). However, decomposition of organic matter that enters the soil mainly relies on microbial activities. Microbial growth and reproduction are significantly affected by soil moisture and temperature conditions (Steiner et al., 2009).

Recent studies have examined the C mineralization (C_{min}) in biochar-amended soils (Bolan et al., 2012; Fernández et al., 2014), mostly in acid soils (Sigua et al., 2014; Zhao et al., 2015). Few studies concerning biochar amendment in saline soils have focused on the effect of temperature on C_{min} in soil. For example, Fang et al. (2014) investigated the temperature sensitivity of biochar-C in soils at 20, 40 and 60 °C in four contrasting soils including Entisol ($pH = 8.77$) and Vertisol ($pH = 7.89$). Presently, there is a limited understanding of moisture response of C_{min} in biochar-amended saline soil. Moreover, it remains unknown whether different amount of biochar applied could alter C_{min} in biochar-amended saline soil under different temperature and moisture conditions.

In this study, the dynamics of C_{min} were monitored in a biochar-amended saline soil from the Yellow River Delta by incubation experiments under different conditions of temperature and moisture. The effects of biochar amendment on C_{min} was examined in the saline soil, in order to understand the mechanisms of C cycle response to environmental changes in biochar-amended saline soil systems.

2. Material and methods

2.1. Soil and biochar

Saline soil was sampled from the 0–10 cm depth at the ecological experimental station of coastal wetland located at Dongying, Shandong Province, China (37°45′ N, 118°59′ E). The soil is a typical saline alluvial soil (Fluvisols, FAO), developed on loess material of the Quaternary period (Liu et al., 2003). The soil sample was sieved though a 2-mm sieve immediately after collection and stored at 4 °C until used. The soil had a pH (H_2O) of 8.5, a C/N ratio of 16.9, and exchanged sodium percentage of 27%.

Biochar was produced from wheat straw. After air-drying with oven, wheat straw was sieved through a 2-mm sieve and charred in a muffle oven at 300 °C for 4 h. Oxygen availability was restricted by wrapping the wood in aluminum foil during heating. The biochar contained 46.3% C and 0.6%N, respectively, with a pH (H_2O) of 6.93.

2.2. Incubation experiments

The incubation experiments included three treatments: (1) soil alone (control), (2) soil added with 2% (w/w) biochar (S + 2%C), and (3) soil added with 4% (w/w) biochar (S + 4%C). Fresh soil sample was sieved through a 2-mm sieve, and mixed with straw and biochar in a 1-L jar (total dry weight 200 g). Soil moisture was adjusted to be 30%, 70% and 105% of the water-holding capacity (WHC; W1, W2, and W3, respectively).

The jars were placed without lids at 15 °C, 25 °C and 35 °C (T1, T2, and T3, respectively) in a thermostat incubator. A rubber plug was used sealed each jar for 24 h at 2, 5, 8, 12, 17, 23, 30, 39, 76, 162, and 220 days. The rubber plug was attached to a glass tube connecting a three-way valve to facilitate gas sampling from the headspace. Gas samples were analyzed for CO_2 concentration within 24 h of collection using Agilent 7890 series gas chromatograph (Santa Clara, CA, USA). Cumulative C_{min} and C_{min} rate were calculated from the difference in CO_2 emission between 0 and 24 h. Each treatment had four replicates. Water evaporation was compensated daily by weighing the jars.

2.3. Data analysis

The rate of C_{min} was calculated as described by Sun et al. (2014). According to the trapezoidal rule, cumulative C_{min} was obtained from the sum of the area bounded by C mineralization rate. The two-compartment model was used to analyze the dependence of cumulative C_{min} on temperature and moisture. The first-order kinetic two-compartment model was fitted by Andrén and Paustian (1987) and described by Reichstein et al. (2000) in detail. It was generally thought that the labile C (C_1) and recalcitrant C (C_2) pools were equal in the same treatment. Temperature primarily affected the C_{min} rate constants (k_1 and k_2, respectively), other than the size, of C_1 and C_2 pools. However, no ideal results could be obtained from the fitting with the experimental data of C_1 and C_2 pools (data not shown). Therefore, we selected the C_1 and C_2 pools as the variables to fit the results of biochar treatments, in order to analyze the mineralization process.

The temperature coefficient (Q_{10}) of C_{min} was calculated using the formula described by Chen et al. (2000). Q_{10} has been used as a constant in most early studies of soil respiration (Xu and Qi, 2001). However, it was later found that the Q_{10} value has great variability from non-sensitive ($Q_{10} < 1$) to extremely sensitive ($Q_{10} > 20$) (Janssens and Pilegaard, 2003; Pavelka et al., 2007). This shows distinct difference from the typical temperature sensitivity ($Q_{10} \approx 2$) based on enzymatic dynamics. Analysis of variation of Q_{10} values in different types of soils has implications for accurately assessing the effect of C_{min} in the soil on CO_2 concentration in the atmosphere.

All data were analyzed using SPSS 13.0 (SPSS Inc., Chicago, IL, USA). Treatment means were separated using *t*-test and mean difference was examined by one-way ANOVA. Two-way ANOVA was applied to test the effects of moisture, temperature and biochar amendment on C_{min}. Statistical tests were considered significant at $P < 0.05$.

3. Results

3.1. Dynamics of cumulative C_{min} in biochar-amended saline soil

Table 1 shows that under different temperature conditions, cumulative C_{min} increased in different treatments with temperature rise. Taking an example S + 2%C treatment, cumulative C_{min} was 377 μg CO_2/g soil at 5 °C, which reached 651 μg CO_2/g soil (72.7% increase) at 25 °C and 1102 μg CO_2/g soil (192% increase) at 35 °C.

Under different moisture conditions, cumulative C_{min} varied in the three treatments. In the control treatment, no significant difference occurred in cumulative C_{min} between 30% WHC and 70% WHC at the indicated temperatures. A remarkable increase was observed only when soil moisture reached 105% WHC ($P < 0.05$).

In the biochar treatments, cumulative C_{min} was highest with 70% WHC, except S + 2%C at 35 °C. For instance, in the S + 4%C treatment at 25 °C, cumulative C_{min} was 668 μg CO_2/g soil with 30%WHC and 693 μg CO_2/g soil with 105% WHC, showing no substantial difference between moisture conditions. When moisture reached 70% WHC, cumulative C_{min} markedly increased to 764 μg CO_2/g soil ($P < 0.05$). However, in the S + 2%C treatment, cumulative C_{min} was highest at 35 °C, which

Table 1
Cumulative C mineralization in saline soil after 220 d of sealed incubation (unit: μg CO_2/g soil).

Biochar treatments	Control	S + 2%C	S + 4%C
T1W1	177a	339a	409a
T1W2	196a	377a	534b
T1W3	226b	266a	443a
T2W1	236b	613b	668c
T2W2	269b	651b	764d
T2W3	363c	634b	693c
T3W1	346c	802c	1255e
T3W2	353c	1102d	1348f
T3W3	409d	1269e	1227e

Note: S + 2%C indicate soil amended with 2% (w/w) biochar; S + 4%C indicate soil amended with 4% (w/w) biochar. W1, W2 and W3 indicate moisture conditions at 30%, 70% and 105% water-holding capacity, respectively; T1, T2 and T3 indicate temperature conditions at 5 °C, 25 °C and 35 °C, respectively.

increased from 1102 μg CO_2/g soil with 70% WHC to 1269 μg CO_2/g soil with 105% WHC.

Meanwhile, cumulative C_{min} displayed substantial differences between treatments ($P < 0.001$). During the 220-d incubation period, the three treatments followed the order: S + 4%C > S + 2%C > control. The cumulative C_{min} in S + 2%C was 266–1269 μg CO_2/g soil, that is, 1.18–3.12 times that in control. The cumulative C_{min} in S + 4%C was 409–1348 μg CO_2/g soil, that is, 1.91–3.82 times that in control. The results of ANOVA revealed that C_{min} was affected by incubation temperature and soil moisture, as well as the amount of biochar amendment in the saline soil (Table 2).

3.2. Kinetics of C_{min} in biochar-amended saline soil

Table 3 shows that the two-compartment model was able to well describe the mineralization process of biochar–soil organic matter within the 220-d incubation period ($R^2 > 0.9$). The concentrations of C_1 ranged from 8.33 to 101 μg/g in different treatments, which only accounted for a small proportion (<0.5%) in the total carbon pool. C_1 gradually increased with temperature rise in the biochar treatments.

The k_1 values were 3–4 orders of magnitude higher than the k_2 values in different treatments, with a k_1/k_2 ratio of 233–7300. This result indicated that the mineralization rate of C_1 was greatly faster than that of C_2. The turnover time of C_1 was in the range of 3–97.1 d, while that of C_2 lasted 18–274 yr. The turnover time of both C_1 and C_2 pools was gradually reduced with temperature rise.

3.3. Q_{10} of C_{min} in biochar-amended saline soil

In this study, the Q_{10} values were compared between different treatments at 15 °C–35 °C (Fig. 1). At the end of the experiment, Q_{10} was 1.24–1.91 for control, 1.3–2.57 for S + 2%C, and 1.57–2.05 for S + 4%C. The values showed major changes in the early stage of incubation, and gradually leveled off in the late stage. A distinct peak appeared at 12–23 d, and the values were generally stabilized after 40 d. Specifically, Q_{10} was maintained at ~1.4 in the control and ~1.7 in S + 4%C at 220 d under the three moisture conditions. For S + 2%C, Q_{10} was maintained at ~1.6 with 30% WHC and 70% WHC, and 2.2 with 105% WHC at 220 d.

Table 2
ANOVA results of three factors influencing C mineralization in saline soil.

Source	d.f.	Sum of squares	Mean square	F	P
Temperature	2	6,063,399	3,031,699	295.58	0.000
Moisture	2	135,664	67,832	6.61	0.002
Treatment	2	5,358,178	2,679,089	261.2	0.000
Temperature × moisture	4	127,988	31,997	3.12	0.019

Under the three moisture conditions, Q_{10} was significantly higher in the biochar treatments compared with control. For example, Q_{10} was 1.26 in the control with 30% WHC, while the corresponding values in the biochar treatments were as high as 1.49 and 1.88. Regardless of biochar amendment, Q_{10} was highest with 105%WHC in the same treatment ($P < 0.05$).

4. Discussion

4.1. Rate of C_{min} in biochar-amended saline soil

In biochar-amended treatments, C_{min} rates were relatively high at the initial stage of incubation and gradually decreased with extended incubation time. This phenomenon was mainly due to the small proportion of C_1 contained in the biochar (Major et al., 2010; Jones et al., 2011). According to the fitting data, the C_1 in biochar used in this study contained <0.5%. After substantial consumption of available substrates, decreased nutrient source became the limiting factor of soil microbial activity (Kuzyakov et al., 2014). Therefore, C_{min} rate decreased in the late stage of the experiment.

The results showed that C_{min} rates gradually increased with increasing amount of biochar added (0–4%, w/w). The increase of C_{min} rates could be attributed to the amendment of the labile C from biochar. Similarly, Knoblauch et al. (2011) found that short-term application of biochar contributed to C_{min} in a 3-year incubation experiment of rice paddy soil. In that study, application of 2.5% biochar resulted in 4.4% and 8.5% increase in cumulative C_{min} under aerobic and anaerobic conditions, respectively.

Additionally, Zimmerman et al. (2011) investigated the effect of weed biochar on Alfisol respiration in Florida, USA. It was found that cumulative C_{min} in early stage was mainly the labile C derived from biochar, in agreement with the finding by Knoblauch et al. (2011). Moreover, Hamer et al. (2004) and Wardle et al. (2008) found that available nutrients contained in biochar improved soil microbial activity and thus contributed to the decomposition of original soil C pool. Smith et al. (2010) assessed the effect of biochar amendment on Shano silt loam soil respiration using $\partial^{13}C$ signature of the biochar, which proved that the decomposition of biochar contributed to an increased amount of C_{min} in the soil.

4.2. Effect of temperature on C_{min} in biochar-amended saline soil

In soil, C_{min} is closely related to temperature change. The two-compartment model fitting result revealed that the concentration of C_1 gradually increased with temperature rise in the biochar treatments. Temperature change can alter the activity, quantity, composition of soil microbial community or the supply of substrates, thereby affecting C_{min} in the soil (Chen et al., 2000; Bergner et al., 2004; Pietikainen et al., 2005). This result suggests that global warming would elevate C_{min} rate in the soil.

Similarly, Ellert and Bettany (1992) and MacDonald et al. (1995) found that the proportion of C_1 pool that can be utilized by soil microorganisms increases with temperature rise. It is possible that temperature induced changes in the composition or activity of microbial communities can modify the biochemical pathways of primary resource exploitation and the production of secondary material, thus consequently affecting the pool size of the resource that `behaves' as labile or recalcitrant. For instance, Zogg et al. (1997) found that this shift in temperature responses were a consequence of changes in the proportions of Gram-positive and Gram-negative bacteria between temperature treatments.

Moreover, temperature can affect the turnover time of soil C pool. As revealed by the fitting result, the turnover time of C_2 pool declined with temperature rise. This observation provides evidence from the other side of point that production of biochar mainly containing recalcitrant C from waste biomass raw materials and subsequent return to the soil

Table 3
Two-compartment model fitting results of cumulative C mineralization in saline soil under different incubation conditions.

Biochar treatments	Incubation condition	C_1 (μg/g)	k_1 (/d)	C_2 (μg/g)	k_2 (/d)	R^2	C_1/C_0 (%)	C_2/C_0 (%)
S + 2%C	T1W1	12.98	0.087	13,748	0.00003	0.998	0.094	99.91
	T1W2	17.5	0.045	13,744	0.00003	0.998	0.127	99.87
	T1W3	8.33	0.039	13,753	0.00002	0.998	0.061	99.94
	T2W1	14.58	0.127	13,747	0.00005	0.999	0.106	99.89
	T2W2	20.4	0.048	13,741	0.00006	0.999	0.148	99.85
	T2W3	9.21	0.058	13,752	0.00006	0.999	0.067	99.93
	T3W1	21.7	0.139	13,740	0.00006	0.999	0.158	99.84
	T3W2	32.4	0.127	13,729	0.00008	0.998	0.235	99.76
	T3W3	51.14	0.083	13,710	0.00008	0.998	0.372	99.63
S + 4%C	T1W1	22.43	0.073	23,561	0.00001	0.998	0.095	99.90
	T1W2	28.5	0.0573	23,554	0.00002	0.999	0.121	99.88
	T1W3	13.6	0.031	23,569	0.00002	0.999	0.058	99.94
	T2W1	42.39	0.056	23,541	0.00003	0.997	0.180	99.82
	T2W2	62	0.041	23,521	0.00003	0.999	0.263	99.74
	T2W3	46.54	0.04	23,536	0.00003	0.999	0.197	99.80
	T3W1	92.57	0.064	23,490	0.00004	0.999	0.393	99.61
	T3W2	101	0.05	23,482	0.00004	0.999	0.428	99.57
	T3W3	100	0.047	23,483	0.00004	0.999	0.424	99.58

Note: S + 2%C indicate soil amended with 2% (w/w) biochar; S + 4%C indicate soil amended with 4% (w/w) biochar; W1, W2 and W3 indicate moisture conditions at 30%, 70% and 105% water-holding capacity, respectively; T1, T2 and T3 indicate temperature conditions at 5 °C, 25 °C and 35 °C, respectively; C_0, C_1 and C_2 are the soil total carbon concentrations, the labile carbon concentrations and recalcitrant carbon concentrations, respectively; k_1 and k_2 are the rate constants of labile and recalcitrant soil C mineralization, respectively.

may have a positive role in mitigating the effect of global warming. However, given the destruction of soil structure during pre-treatment, the results of organic carbon turnover time obtained from the laboratory experiment were only used for comparative analysis between treatments. These data could not represent the actual turnover time of biochar amended to field soils.

4.3. Effect of moisture on C_{min} in biochar-amended saline soil

In the control experiment (soil alone), a remarkable increase occurred in cumulative C_{min} only when soil moisture reached 105% WHC. In the biochar treatments, however, 70% WHC was optimal for C_{min} (except S + 2%C, 35 °C). It is possible that the dominant soil microbial populations capable of decomposing biochar are different from those metabolizing the original soil organic matter (Pietikainen et al., 2000; O'Neill et al., 2009). The considerably low biomass under flooded and low-temperature conditions might have limited the adjustment of microbial community diversity. Grossman et al. (2010) found population structure difference in >90% of soil bacteria and archaea between biochar-amended black soil and adjacent non-biochar soil in Amazon. Moreover, Hu et al. (2014) compared bacterial and fungal communities between biochar-amended red soil and non-biochar control soil after 96 d of incubation. It was found that the effect of biochar amendment was significant for the composition and abundance of soil microbial communities. These findings taken together indicate that soil microbial communities adapted to wetland soil conditions (flooding conditions) take a certain period of time to metabolize exogenous organic matter substrates.

In this study, the flooding and low-temperature conditions applied were unfavorable for adjusting the structure of soil microbial communities, thus resulting in a relatively low cumulative C_{min}. By comparison, 70% WHC was conducive to the diffusion of soluble organic matter. Together with better soil permeability and high microbial activity contributed to a higher cumulative C_{min}. An exception was S + 2%C treatment at 35 °C, which had higher cumulative C_{min} with 105% WHC, compared with 70% WHC. This result suggests that adding an appropriate amount of biochar could reduce the impact of flooding on soil C_{min} at higher temperature. It is possible that soil microbial activity is relatively high under high-temperature conditions, and the corresponding microbial community is thus rapidly formed. These microbial components could metabolize soil organic matter and biochar-derived available nutrients, improve soil permeability, and thereby elevate C_{min} rates (Cheng et al., 2006; Brodowski et al., 2006).

A comparative analysis of Q_{10} between the three moisture conditions showed that Q_{10} were highest with 105%WHC in the same treatment, reaching a significant level. The underlying mechanism may be that soil water film is thinner under lower moisture condition, thus limiting the diffusion of substrates and extracellular enzymes and migration of microbes (Davidson and Janssens, 2006). As a consequence, the opportunity of microbe to contact substrate is reduced, leading to lower temperature sensitivity of soil respiration (McCulley et al., 2007). In other words, although temperature rise accelerates C_{min} rate in soil, drought may reduce or offset the temperature effect, as has been reported by Reichstein et al. (2005) and Gaumont-Guay et al. (2006).

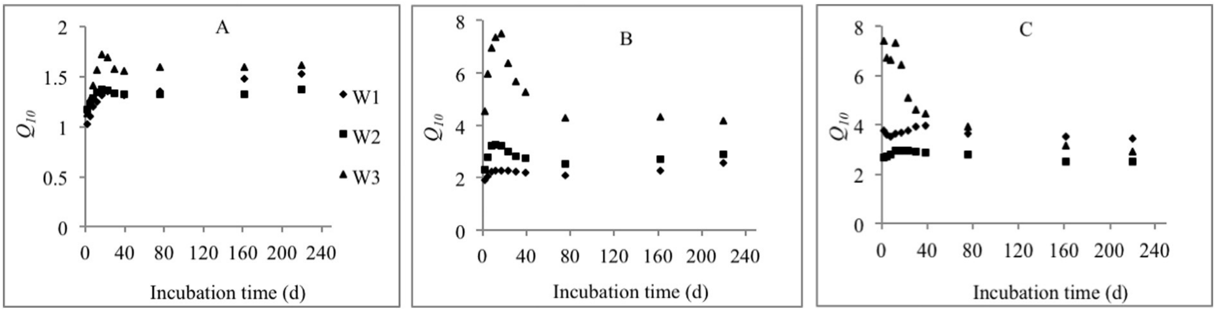

Fig. 1. Temperature sensitivity (Q_{10}) of carbon mineralization in saline soil under different incubation conditions (15–35 °C). Note: A: soil alone (control); B: soil amended with 2% (w/w) biochar (S + 2%C); C: soil amended with 4% (w/w) biochar (S + 4%C). W1, W2 and W3 indicate three moisture conditions, 30%, 70% and 105% of the water-holding capacity, respectively.

5. Conclusions

Temperature, moisture, and the amount biochar added significantly affected C_{min} in saline soil of the Yellow River Delta. Amendment of biochar containing labile C contributes to a higher mineralization rate in the early stage, whereas a relatively low C_{min} rate in the late stage is conducive to the accumulation of soil organic matter. During sealed incubation, cumulative C_{min} consistently increases with increasing amount of biochar added (0–4%) and incubation temperature (15 °C–35 °C). However, cumulative C_{min} follows different trends under varying moisture conditions (30–105% WHC). The results indicate that an appropriate amount of biochar amendment is favorable for attenuating the impact of flooding on C_{min} in soil. This study has reference value for establishing a dynamic model of C, predicting the dynamic changes of soil C content, and regulating C pool in saline soil systems.

Acknowledgements

This research was supported by the project of Ludong University (LY2015013), National Natural Science Foundation of China (41501309; 41271236), Jiangsu Agricultural Science and Technology Innovation Fund (CX(15)1005), the National Basic Research Program of China (2013CB430403), Shuangchuang Talent Plan of Jiangsu Province, Yantai Double-hundred Talent Plan (XY-003-02), and 135 Development Plan of YIC-CAS.

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