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Effects of Drying-Rewetting Frequency on Vertical and Lateral Loss of Soil Organic Carbon in a Tidal Salt Marsh

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Abstract

Tidal salt marshes, as "blue carbon" ecosystems, play a critical role in mitigation of global climate change since their large soil organic carbon (SOC) pool. Drying-rewetting cycles induced by periodic tides have profound influence on soil carbon cycling in tidal salt marshes. However, the magnitude and mechaanism of the effects of drying-rewetting frequency on SOC loss in tidal salt marshes is still uncertain. Here, we conducted a mesocosm experiment to identify how drying-rewetting frequency changes alter the vertical (CO_2 and CH_4) and lateral (dissolved organic carbon) carbon losses of soils in a tidal salt marsh in the Yellow River Delta (YRD). We found that increasing soil moisture inhibited CO_2 emission but stimulated CH_4 emission in a tidal salt marsh. Soil dissolved organic carbon (DOC) was produced in the drying phase and rewetting lead to the loss of DOC. Soil moisture and salinity change induced by drying-rewetting cycles were the critical factors controlling vertical organic carbon loss in a tidal salt marsh. DOC had significant effects on CO_2 emissions. Changes of tidal action and drying-rewetting cycle induced by global change can affect the pathway of carbon loss in a tidal salt marsh.

Keywords Tidal salt marshes · Drying-rewetting cycle · CO_2 and CH_4 emissions · Dissolved organic carbon

Introduction

Tidal salt marshes have been termed as one of the most important "blue carbon" ecosystems. They are efficient in sedimentation and trapping associated soil organic carbon (SOC)

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during tidal inundation (McLeod et al. 2011). Though the global area is much smaller than other types of ecosystem, e.g., forest or grassland, the carbon sequestration rates of "blue carbon" ecosystems are much greater than those of terrestrial ecosystems (McLeod et al. 2011; Lovelock et al. 2017; Ouyang et al. 2017). Carbon can be sequestered in salt marshes at a rate nearly 40 times higher than that in tropical rainforests (Duarte et al. 2005). Accordingly, "blue carbon" ecosystems, in particular tidal salt marshes, are critical for the global carbon cycle and the mitigation of climate change, which is noteworthy in the future (Howard et al. 2017; Macreadie et al. 2017).

The tidal salt marsh serves not only as a long-term carbon sink, but as a potential carbon source once the ecosystem is lost or degraded (Fellman et al. 2017; Howard et al. 2017; Lovelock et al. 2017; Macreadie et al. 2017). There exist two pathways for carbon loss in tidal salt marshes, namely vertical and lateral carbon loss (Evans et al. 2015; Fellman et al. 2017). Vertical carbon loss, including CO_2 and CH_4 emissions, is generally considered as a major contributor to soil carbon loss of terrestrial ecosystems (Liu et al. 2017). However, lateral carbon loss of tidal salt marsh obviously cannot be ignored because of regularly tidally flooding and

scouring effect of periodical tides (Maher et al. 2013; Howard et al. 2017). Dissolved organic carbon (DOC) is recognized as one of the dominant forms of lateral carbon loss from terrestrial ecosystems to aquatic ecosystems (Billett et al. 2010; D'Amore et al. 2015). Besides, as a labile component of SOC, DOC is still found to have a close correlation with soil carbonic greenhouse gas formations (Fellman et al. 2017; Liu et al. 2017; Lee et al. 2018; Qu et al. 2018). Thus, both lateral and vertical carbon loss from tidal salt marshes soil to ocean and atmosphere, respectively, should be considered into "blue carbon" loss of salt marshes.

Drying-rewetting cycle and its induced surface accumulation and leaching of salt are considered the most prominent characteristics differentiating the tidal salt marsh from other wetland ecosystems (Chambers et al. 2013). In recent years, tidal salt marshes have been seriously disturbed or even damaged by many anthropogenic and natural factors (Kirwan and Megonigal 2013; Tian et al. 2016), including sea level rise (IPCC 2014), dam construction (Kirwan and Megonigal 2013), and invasions of exotic plants (Yuan et al. 2015), which lead to the changes in soil drying-rewetting frequency of tidal salt marsh (Morillas et al. 2015). Changes in drying-rewetting frequency can affect soil SOC loss through influencing soil moisture, salinity and other physio-chemical properties, and the microbial activity. In general, drying always produced positive effects on CO_2 production and negative effects on CH_4 formation because of the aerobic conditions in wetlands (Olsson et al. 2015; Liu et al. 2017). Moreover, decomposition of SOC always fluctuate with soil drying-rewetting cycles, because that the microbes always respond quickly to the changes of soil moisture and salinity during drying-rewetting cycles (Moyano et al. 2013; Yemadje et al. 2016). For instance, Birch Effect always observed with a rewetting event after extreme drying as a result of rapid excitation of microbial activity (Birch 1958; Mavi and Marschner 2012). In fact, the increase in salinity usually reduces SOC loss as salinity negatively affects soil microbial activity (Chambers et al. 2013). However, some other studies showed that an increase in salinity can promote soil respiration by generating cellular osmotic stress (Saviozzi et al. 2011; Drake et al. 2014). In addition, drying-rewetting also leads to a release of DOC, as a result of the weakened protective effect to SOC from soil aggregates. Furthermore, the drier the soil, the more DOC would be released after rewetting (Xiang et al. 2008; Gaelen et al. 2014). However, for these previous experiments were mostly concentrated on the effects of drying-rewetting cycles on arid ecosystems, the effects on SOC loss in tidal saltmarshes is still not clear.

The Yellow River Delta (YRD) is one of the world's most active and the youngest coastal wetland, which is affected by land-ocean interactions (Qin et al. 2010; Han et al. 2014). Salt marsh in the YRD, a newly formed coastal wetland, held great potential of carbon sequestration, yet it also can be a huge carbon source in the face of changes of hydrodynamics (Ye et al. 2016). Accordingly, the YRD become an ideal area to investigate the effects of drying-rewetting frequency on SOC loss in tidal salt marsh. The aims here were (1) to make the determination of soil vertical (CO_2 and CH_4) and lateral (DOC) carbon loss under different drying-rewetting frequency treatments in tidal salt marsh; (2) to investigate the effects of soil properties on emissions of CO_2 and CH_4 and DOC production; (3) to demonstrate the effects of varying soil DOC concentration on CO_2 and CH_4 emissions in this study.

Materials and Methods

Site Description

This study was performed using soil from a tidal salt marsh in the YRD (37°35′–38°12′N, 118°33′–119°20′E), Shandong, China. It has a warm temperate and continental monsoon climate with distinctive seasons and distributions of rain and heat. The annual average temperature is about 12.9 °C, and the annual average precipitation is about 640 mm and mainly concentrates in summer (from June to September). According to the flooding characteristics of the tidal flat, the area could be divided into high marsh, middle marsh and low marsh. Tide in low marsh is irregular semidiurnal (twice a day), while the high marsh was affected by tidal flooding twice a month. The mean tidal range from 0.73 m to 1.77 m. The salinity of sea water ranges from 26‰ to 30‰ (Song et al. 2013). The marsh soil is largely covered by Fluvo-aquic soil and saline soil (Jia et al. 2017). The chemical and physical properties of topsoil (0–10 cm) in the salt marsh are listed in Table 1.

Soil Collection and Preparation

Four 1 m × 1 m typical quadrats in the *Suaeda salsa* (*S. salsa*) marsh in the high marsh in the YRD were selected as the study

Table 1 Soil physio-chemical properties of surface soil in a salt marsh in Yellow River Delta (mean ± standard error, $n = 3$)

Parameters	Original soil
pH	8.66 ± 0.02
Salinity (mg g^{-1})	14.73 ± 0.29
Dissolved organic carbon (DOC) (mg g^{-1})	0.03 ± 0
Total organic carbon (TOC) (mg g^{-1})	2.96 ± 0.04
Total carbon (TC) (mg g^{-1})	16.04 ± 0.3
Total nitrogen (TN) (mg g^{-1})	0.34 ± 0.01
C: N ratio (C/N)	8.66 ± 0.41
Clay fraction (%)	6.48 ± 0.04
Silt fraction (%)	37.66 ± 0.23
Sand fraction (%)	55.86 ± 0.21

sites in September 2017. 90 intact soil cores (30 cm tall, 16 cm diameter) were collected from the four plots by pushing PVC tubes (50 cm tall, 16 cm diameter) into the depth of 30 cm. All the soil cores were collected in two days. All soil cores with PVC tubes were immediately transported to the Yellow River Delta Ecology Research Station of Coastal Wetland, Chinese Academy of Sciences, and plastic base was installed at the bottom of each PVC tube to prevent the loss of soil and water. To ensure consistency, all the soil cores were wet with the same quantity of water and pre-incubated for 5 days before the experiment.

Setup of Mesocosm Experiments

After pre-incubation, soil cores were immediately incubated for additional 60 days. All soil cores were stratified into two parts: one part was used for gas sampling; the other part was for destructive harvests. In tidal salt marshes in the YRD, low tide flat can be flooded by tidal seawater once a day, while high tide flat can only be flooded approximately once a month (Jia et al. 2017). Besides, some area of tidal salt marshes was turned into dry land and would never be flooded by tide due to the construction of anthropogenic barriers. Therefore, five treatments of drying-rewetting frequency were set to simulate tidal flats with different elevations: (1) CM (constantly moist): the soil cores were watered per day; (2) 5D: twelve cycles of 5-day air drying events, separated by 12 rewetting events; (3) 15D: four cycles of 15-day air drying events, separated by 4 rewetting events; (4) 30D: two cycles of 30-day air drying events, separated by two rewetting; (5) CD (continuously dry): the soil cores were naturally desiccated during the whole incubation. In the drying phase, soil was air dried naturally. At the end of each drying phase, soil cores were rewetted, and the water level was kept at 10 mm for 8 h. Subsequently, the remaining water on soil surface was eliminated by ear syringe.

Sample Collection and Analyses

Each treatment involved 24 replicates. Three replicates of each treatments were used to quantify CO_2 and CH_4 emission rates during 60-d incubation, and a silicone tube with a valve was placed on the empty upper part of those cores. During incubation, CO_2 and CH_4 emission rates were measured the day before and after each rewetting event. Each time, five 30 ml chamber air samples were automatically pulled into air bags through a gas pump at 0, 5, 10, 15 and 20 min after closure. Next, they were transferred into 12 ml pre-evacuated vials that were fitted using butyl rubber stoppers for the purpose of study. To balance the air pressure between outside and inside the PVC tube in sampling, the empty upper part of each core was equipped with a thin plastic air bag to connect with the outside via a tube. At the same time, the temperature of the chamber's air was measured using an automatic temperature recorder. With the use of a gas chromatograph (Agilent 7890, Santa Clara, CA, USA) coupled with a flame ionization detector, CO_2 and CH_4 concentrations were determined. In accordance with the repeated measurements of standard samples, the precisions of CO_2 and CH_4 levels were both 0.5%. With the use of a linear least square fit to the five points in the time series of concentration for each soil core, CO_2 and CH_4 fluxes were calculated. Since CO_2 and CH_4 levels were determined every two or three days, their emission rates during sampling intervals were assumed to be equal to the average of the two emission rates from the two sampling events in the calculation of the average emission rates.

For soil physio-chemical properties, three replicates of each treatment were terminated at 0, 6, 16, 31, 46, and 60-d and 0–10 cm soils were collected. Gravimetric water content was measured by oven drying fresh subsamples at 105 °C until the dry weight was constant in a forced air oven. The remaining soil was air dried, crushed and stratified into two subsamples. One subsample was sieved through a 2-mm sieve in order to test the soil pH, salinity and texture, and the other was sieved through a 0.15-mm mesh to determine the concentration of total carbon (TC), total nitrogen (TN), total organic carbon (TOC) and DOC. Soil salinity and pH were measured with an electricity conduction meter and a pH meter (soil: water = 1: 5), respectively. Using distilled water (1:5 soil water ratio), DOC in the soil was extracted and shaken for 1 h at ambient temperature, followed by centrifugation at 6000 rpm for 25 min. Then, the supernatant underwent filtering via a 0.45 μm filter (Millipore Express). The concentration of DOC was measured with a TOC analyzer (TOC-VCPN, Shimadzu, Japan). In TOC analysis, for the removal of carbonates, this study gave the overnight treatment to soil samples using 1 mol L^{-1} HCL. After oven drying at 60 °C, the samples were ground to 0.15-mm mesh underwent TOC analysis under the use of an element analyzer (Vario Micro cube, Elementar, Germany). Likewise, TC and TN were both measured with the element analyzer. With the use of a laser particle size analyzer (Marlvern Mastersizer 2000F, Malvern, UK), Grain size composition was studied. Subsequently, three categories were distinguished: < 2 μm for clay, 2–20 μm for silt and > 20 μm for sand.

Statistical Analysis

To identify the differences in average emission rates of CO_2 and CH_4, DOC concentration, we performed one-way ANOVA analysis. $p < 0.05$ was considered significant. Stepwise multiple regression and correlation analysis were performed to study the correlations of CH_4 and CO_2 emissions and DOC concentration with soil properties, and the correlations between soil properties. Statistics were studied using

SPSS 19.0 (SPSS Inc., Chicago, IL, USA). Figures were drawn using Sigmaplot 12.5 (Systat Software Inc.).

Results

Effects of Changes of Drying-Rewetting Frequency on CO_2 and CH_4 Emissions

Increasing frequency of drying-rewetting cycles significantly decreased CO_2 emission and increased CH_4 emission (Fig. 1a and c). Drought produced significantly positive effect on CO_2 emission but negative effect on CH_4 emission. The average rates of CO_2 emission before rewetting in all drying-rewetting treatments were significantly higher than those after rewetting (Fig. 1b). Furthermore, the differences between the average rates of CO_2 emission before and after rewetting were higher in lower frequency drying-rewetting treatments. CH_4 emission was induced by rewetting events. The average rates of CH_4 emission before rewetting in all drying-rewetting treatments were significantly lower than those after rewetting (Fig. 1d). The difference between the average rates of CH_4 emission before and after rewetting was 49.10 μg CH_4 m^{-2} h^{-1} at 30D treatments, much higher than that at 5D and 15D.

CO_2 emission rates significantly increased with TN ($p < 0.001$), TOC ($p = 0.001$), sand fraction ($p = 0.01$) and salinity ($p = 0.01$). In contrast, CO_2 emission rates had a significant and negative correlation with gravimetric water content ($p = 0.001$), silt fraction ($p = 0.008$) and clay fraction ($p = 0.04$), yet they were not dependent on pH, TC and C/N ($p > 0.05$). The stepwise multiple regressions (Table 3) showed that CO_2 emissions were significantly impacted by DOC ($p < 0.001$), gravimetric water content ($p < 0.001$) and TOC ($p = 0.01$).

CH_4 emission rates were strongly positively related to soil gravimetric water content ($p < 0.001$), TC ($p < 0.001$), TOC ($p < 0.001$), TN ($p = 0.001$) and clay fraction ($p = 0.04$). CH_4 emissions and salinity were found to be significantly negative related ($p < 0.001$). CH_4 emission rates were not correlated with some of the soil properties (e.g., pH, C/N, silt fraction and sand fraction). According to the stepwise multiple regressions (Table 3), CH_4 emissions were significantly impacted by gravimetric water content ($p < 0.001$) and TC ($p < 0.001$).

Effects of Changes of Drying-Rewetting Frequency on Soil DOC Formations

At the end of incubation, significant differences in soil DOC concentration among all the treatments were observed (Fig. 2). Among the 3 drying-rewetting treatments, DOC concentration was lower in the drying-rewetting treatment with longer drying phase. Nevertheless, the lowest DOC concentration was 0.0156 mg g^{-1} in the CM, and the highest reached 0.02 mg g^{-1} in the CD.

Fig. 1 Cumulative CO_2 (**a**) and CH_4 (**c**) emissions under different treatments over the whole incubation period. Average soil gas emission rates before (solid bar) and after (empty bar) rewetting events under 5D, 15D and 30D treatments are also presented for CO_2 (**b**) and CH_4 (**d**). Bars and vertical lines represent means and SE. Letters represent significant differences between treatments at $p < 0.05$. '**' indicates significant differences between the two conditions at $p < 0.01$, '***' indicates significant differences between the two conditions at $p < 0.001$
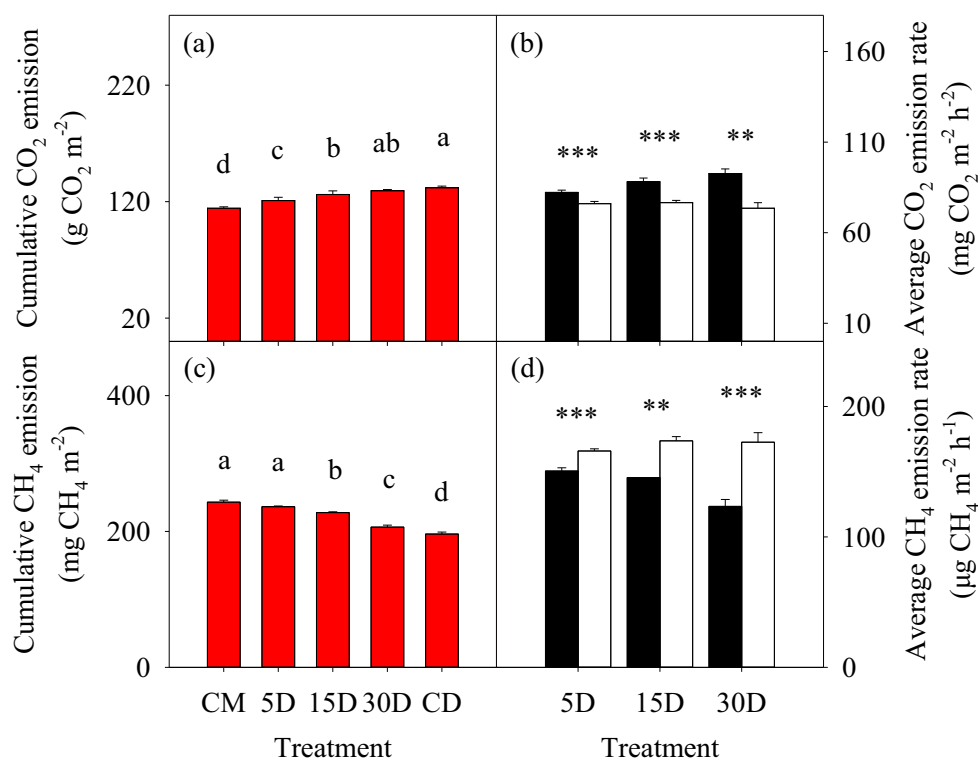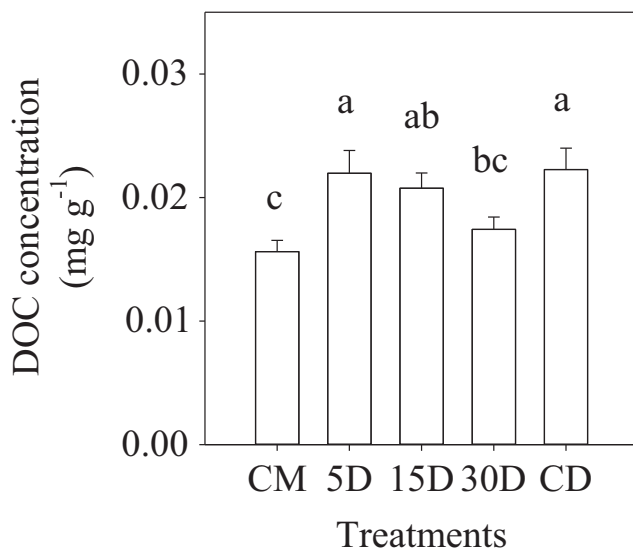
Fig. 2 Average DOC concentrations at the end of incubation under different treatments. Bars and vertical lines represent means and SE. Letters represent significant differences between treatments at $p < 0.05$

Based on the correlation analysis, soil DOC content was positively influenced by salinity, TOC, TC, TN and sand fraction, while it was negatively influenced by soil gravimetric water content, pH, C/N ratio, clay and silt fraction (Table 2). However, only TOC (p < 0.001), TN (p < 0.001), C/N ratio ($p = 0.04$), clay ($p = 0.02$) and silt (p < 0.001) content were significantly correlated with soil DOC concentration. The linear regressions indicated that soil DOC concentration was positively correlated with soil TOC and TN contents (Fig. 3). According to the stepwise multiple regressions (Table 3), DOC was significantly influenced by TN (p < 0.001), TC ($p = 0.002$) and pH ($p = 0.02$).

Relationships between CO_2 and CH_4 Emissions Rates and DOC Concentrations under Different Drying-Rewetting Frequency

For the determination of the impacts of DOC on soil CO_2 and CH_4 emissions, the regression analysis was performed (Fig. 4). According to the result, DOC had a close linear relation with soil CO_2 emission rates ($r^2 = 0.28$, $p < 0.0001$), while it was not closely correlated with soil CH_4 emission rates here ($p > 0.05$). Besides, both the correlation analysis and the stepwise multiple regression showed that DOC was the most influential soil properties in the formation of CO_2, while the result of the stepwise multiple regression suggested that DOC concentration and CH_4 emission rates were not significantly correlated (Table 3).

Effects of Changes in Drying–Rewetting Frequency on Soil Organic Carbon Loss

The relationships of the cumulative CO_2 and CH_4 against soil gravimetric water content and salinity were examined to assess the influences of soil moisture and salinity on loss of soil vertical carbon loss (Fig. 5). Quadratic relationship was observed between cumulative CO_2 emissions and soil moisture ($r^2 = 0.95$, $p = 0.05$, Fig. 5a). Cumulative CO_2 emissions increased with soil moisture before soil gravimetric water content reached 22% and then declined with the further increase in soil moisture. In addition, the linear regressions indicated that cumulative CO_2 emissions were positively correlated with soil salinity ($r^2 = 0.83$, $p = 0.03$, Fig. 5b). Cumulative CH_4 emissions were increased with the increase of soil moisture ($r^2 = 0.98$, p = 0.02, Fig. 5c) while decreased linearly with soil salinity ($r^2 = 0.82$, p = 0.03, Fig. 5d).

Table 2 Correlation coefficients of CO_2 emission rate, CH_4 emission rate and DOC concentration with soil physio-chemical properties

	CO_2	CH_4	DOC	Gravimetric water content	Salinity	pH	TOC	TC	TN	C/N	Clay	Silt	Sand
CO_2	1												
CH_4	−0.10	1											
DOC	0.53**	0.05	1										
Gravimetric water content	−0.34**	0.49**	−0.12	1									
Salinity	0.26*	−0.43**	0.09	−0.68**	1								
pH	−0.06	0.12	−0.12	0.31**	−0.33**	1							
TOC	0.33**	0.38**	0.43**	0.25*	−0.36**	0.07	1						
TC	0.10	0.49**	0.19	0.26*	−0.46**	0.08	0.65**	1					
TN	0.37**	0.35**	0.60**	0.12	−0.25*	0.12	0.80**	0.64**	1				
C/N	−0.04	0.13	−0.22*	0.27	−0.24*	−0.02	−0.45**	0.12	−0.17	1			
Clay	−0.21*	0.22*	−0.26*	0.38**	−0.15	0.02	−0.06	0.03	−0.17	0.17	1		
Silt	−0.28**	0.13	−0.40**	0.38**	−0.16	0.01	−0.16	−0.05	−0.33**	0.24**	0.91**	1	
Sand	0.27*	−0.14	0.38**	−0.39**	0.16	−0.01	0.15	0.04	0.31**	−0.23**	−0.93**	−0.99**	1

* Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed). DOC represents dissolved organic carbon, *TOC* represents total organic carbon, *TC* represents total carbon, *TN* represents total nitrogen
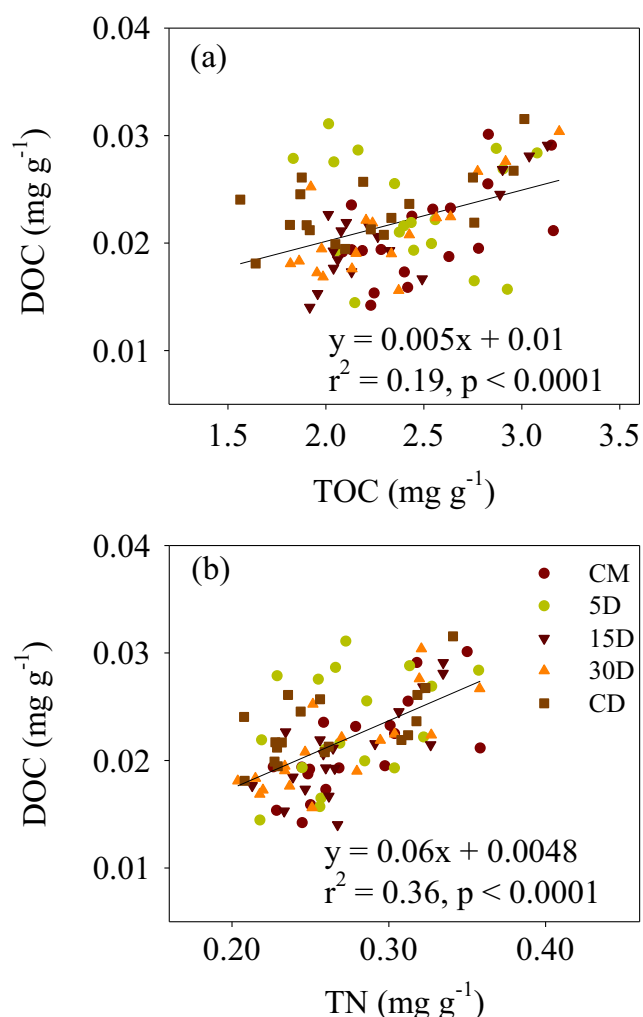
Fig. 3 Regressions of soil DOC concentrations ($n = 90$) with TOC (a), TN (b), C/N (c) across the 60-d laboratory incubations. The scattered points represent data measured in each mesocosm

Discussion

### Effects of Drying-Rewetting Cycles on Soil Vertical Carbon Loss

Soil vertical carbon loss was highly determined by soil moisture here. Obviously, average CO_2 emissions over the treatment phase for soil with lower frequency of drying-rewetting cycles were much greater than those exposed to higher drying-rewetting cycles (Fig. 1a). An increase in water content exceeding the optimum value always led to the reduction in CO_2 emissions because of the limited diffusion and oxygen stress (Jimenez et al. 2012; Malone et al. 2013). Previous studies performed in many other wetland ecosystems also showed very low CO_2 emission rates after rewetting (Jimenez et al. 2012; Miao et al. 2017). During drying period, oxygen availability was promoted by deepening the depth of soil oxygenation and promoting gas diffusion, which further resulted in an increase in CO_2 emission rates with the increase of metabolic activity of aerobic organisms (Malone et al. 2013; Webster et al. 2013; Olsson et al. 2015). Thus, the SOC loss in the form of CO_2 in tidal salt marsh was strongly induced by the decrease of soil moisture with the decrease of frequency of drying-rewetting cycle (Fig. 5a). In contrast, under water saturation after rewetting, biological activity of methanogens was significantly boosted under anaerobic condition, which could lead to a rise of CH_4 production (Kim et al. 2012; Webster et al. 2013). After rewetting, drying caused a decrease in CH_4 emissions (Fig. 1d). Prior studies in wetland ecosystems has found that both rates of CH_4 diffusion out of soil rates and oxidation rates increased when oxygenation went deeper (Malone et al. 2013; Olsson et al. 2015; Smith et al. 2018), which even made the soils a sink for CH_4 (Bachoon and Jones 1992).

Besides, the results here showed that soil salinity had a strong negative correlation with CH_4 emissions (Fig. 5d). However, this is contrary to CO_2 (Fig. 5b). In general, salinity changes microbial community structure and has a strong negative impact on soil microbial activities, microbial biomass

Table 3 Stepwise multiple regression of CO_2, CH_4 emissions and DOC concentrations with soil physio-chemical properties

	Variables entered and p values	Regression equation	Multiple correlation coefficient	F and p values
CO_2	1. DOC, $p < 0.001$ 2. Gravimetric water content, $p < 0.001$ 3. TOC, $p = 0.01$	$CO_2 = 0.38$DOC - 0.36Gravimetric water content +0.26TOC	0.64	20.01, $p < 0.001$
CH_4	1. Gravimetric content, $p < 0.001$ 2. TC, $p < 0.001$	$CH_4 = 0.39$Gravimetric water content + 0.39TC	0.62	26.51, $p < 0.001$
DOC	1. TN ratio, $p < 0.001$ 2. TC, $p = 0.002$ 3. pH, $p = 0.019$	DOC = 0.82TN - 0.33TC -0.192pH	0.68	24.16, $p < 0.001$

DOC represents dissolved organic carbon, *TOC* represents total organic carbon, *TC* represents total carbon
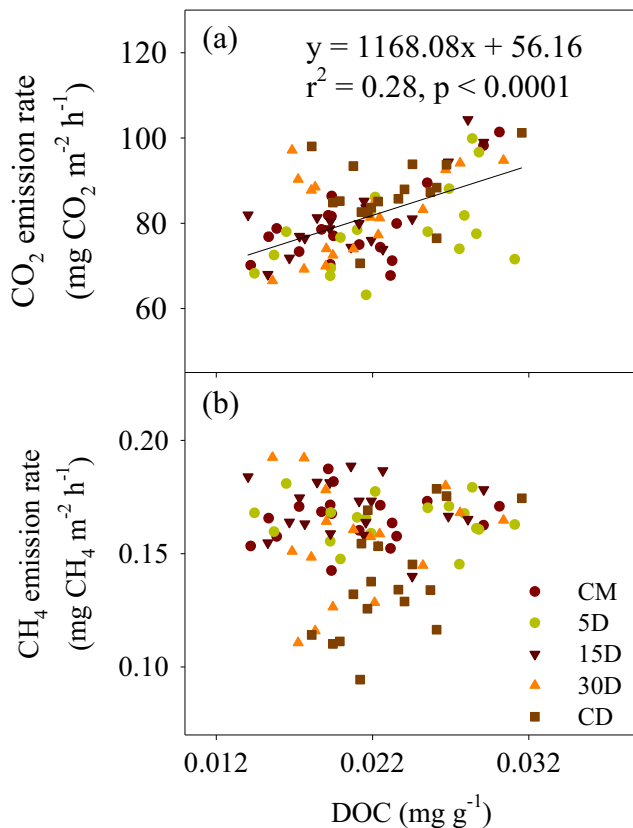
Fig. 4 Relationships of CO_2 and CH_4 emission rates ($n = 90$) with soil DOC concentrations across 60-d laboratory incubations. The scattered points represent data measured in each mesocosm

and enzyme activities (Chambers et al. 2013; Yan and Marschner 2013; Chambers et al. 2016). It further reduces the decomposition of SOC (Quintino et al. 2009; Poffenbarger et al. 2011). However, the correlation of CO_2 production with soil salinity here was inconsistent with numerous studies, which found the increase in salinity followed by a suppression of CO_2 production (Chambers et al. 2013). Soils with varying salinity caused by drying-rewetting cycles often differ in many other physio-chemical properties e.g., moisture content, texture and SOC content, which makes it hard to isolate the effect of salinity on soil CO_2 production from that of other factors (Yan and Marschner 2013). A previous study demonstrated that soil respiration was highly determined by soil moisture at elevated soil salinities (Drake et al. 2014). Salinity of surface soil always varies with soil moisture content and increases as the moisture content decreases during long drying period (Yan and Marschner 2013). The results revealed that soil moisture content was more important in controlling the CO_2 formations than salinity during drying-rewetting cycles, resulting in an overall rise of CO_2 emissions along the increase in salinity.

Moreover, besides soil moisture and salinity, changes of many other physio-chemical properties induced by drying-rewetting cycles, e.g., SOC and nutrients content, also affect

the soil vertical carbon loss by changing water retention, pore space and microbial activities (Harrison-Kirk et al. 2013; Moyano et al. 2013). It is generally accepted that production of CO_2 and CH_4 tends to increase with the increase of SOC content because of its critical role in substrate supply for microbes (Harrison-Kirk et al. 2014). Here, the highest rate of CO_2 emission rate appeared in CD treatment at the end of the incubation because of reduction of moisture content, though the SOC content was relatively low (Data not shown). Hence, it seems to be more complex when describing the effect of SOC content on CO_2 production under drying-rewetting cycles, while it was always considered a positive correlation between them at a fixed moisture value (Butterly et al. 2010; Harrison-Kirk et al. 2013).

Effects of Drying-Rewetting Cycles on Soil Lateral Carbon Loss

Soil DOC in coastal wetlands was always thought to be one of the main forms of lateral carbon loss from land to ocean through tidal export because of its high mobility (Fellman et al. 2017; Ray et al. 2018). Though soil DOC comprises only a small part of SOC, it has a significant impact on blue carbon pool in tidal salt marshes (Mavi and Marschner 2012; Barrón and Duarte 2016). Soil DOC concentration after 60-d incubation was highest in the CD treatment and lowest in the CM treatment (Fig. 2). This may be related to the following mechanisms. First, a previous study indicated that more DOC was released from drier soil (Gaelen et al. 2014). Second, there was no leaching or lateral export in CD treatment during incubation because of continuously drying. Moreover, soil DOC concentration after incubation was decreased with the frequency of drying-rewetting events (Fig. 2), which was probably because DOC produced in drying period was consumed by microbes after rewetting, as observed in other studies (Wu and Brookes 2005; Butterly et al. 2009). As a type of labile fraction of SOC, DOC generally decreased with the decrease in SOC, as reported in many field studies (McDonald et al. 2017; Zhao et al. 2018), which was also observed in our study.

Contribution of DOC to CO_2 and CH_4 Formations

A close linear relation between CO_2 emission rates and DOC concentration has been observed here (Fig. 4a). The correlation coefficient between soil DOC and CO_2 emission rates was strongly higher than that between soil TOC and CO_2 rates (Table 2). Hence, it was concluded that DOC, the active part of SOC, was first utilized by microbes, and only a minor extent of CO_2 came from the decomposition of the recalcitrant part according to the observations in some previous studies (Liu et al. 2017; Lee et al. 2018). In soil, dissolved organic matter is the most easily decomposable C source since soil microbes are almost aquatic and the availability of SOC

determined by soil water environment (Marschner and Kalbitz 2003). However, many other studies found that significantly positive relationships between DOC concentrations and CO_2 emissions can only be observed in the first few weeks of a long-term incubation, while it showed a decrease over time because of the depletion of DOC (Fellman et al. 2017; Qu et al. 2018). Furthermore, some previous study showed that CO_2 emissions were also primarily determined by DOC bioavailability (Fellman et al. 2017; Liu et al. 2017), which deserves to be specially focused in further studies.

Compared to CO_2 emissions, no association was observed here between DOC concentration and CH_4 emission rates (Fig. 4b). Though it was always weaker than that of DOC and CO_2, the positive relationship between DOC and CH_4 was found in previous studies (Said-Pullicino et al. 2016; Liu et al. 2017). DOC could be exploited by methanogens under anaerobic conditions. However, a previous incubation found that the correlation curve of DOC and CH_4 increased absolutely slow if the DOC concentration was low, while the curve increased sharply if the DOC concentration was high (Liu et al. 2017). Thus, one of the possible reason accounting for the results here might be the lack of DOC. For another, the critical reason for the inconsistency of results between our study and previous studies might be the changes of redox condition during drying-rewetting cycles since methane production requires a strictly anaerobic environment (Olsson et al. 2015).
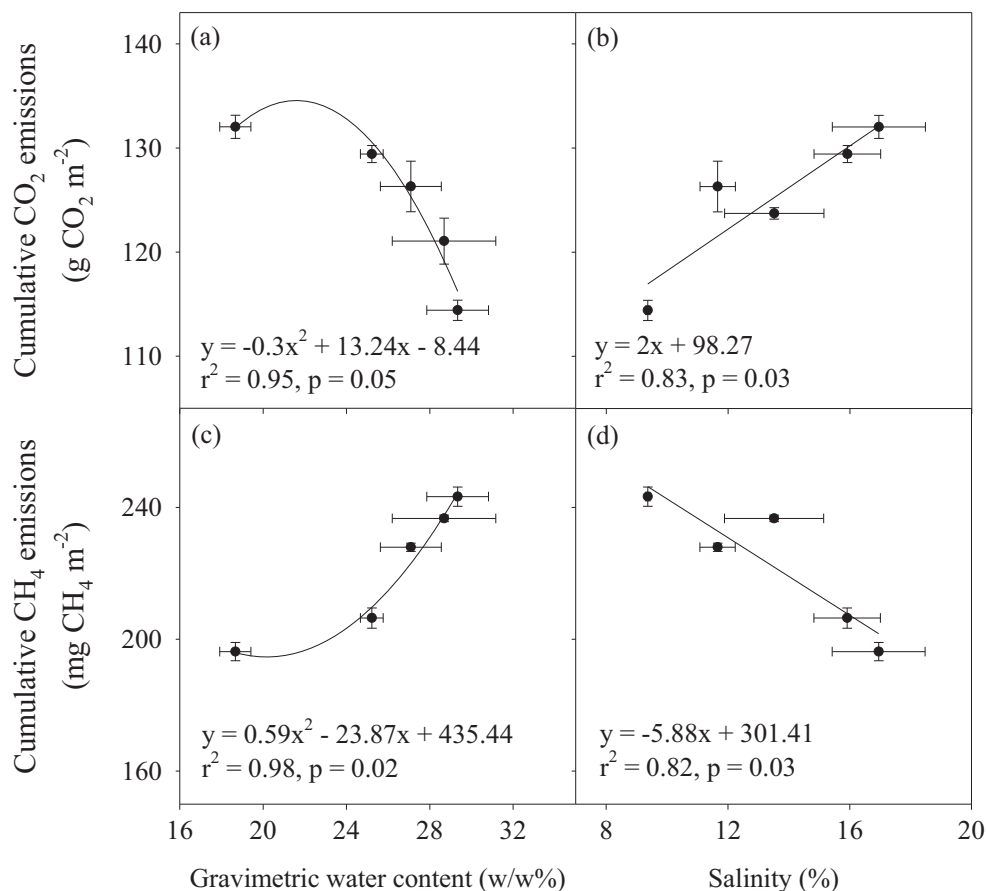
Limitation and Suggestions for Management

By a laboratory experiment, this study determined the response of SOC losses to changed drying-rewetting frequency in tidal salt marshes. This method can limit the variability of other controlling factors, such as air temperature and SOC content. Furthermore, it is convenient to measure the gas emission rates at any time, which bring us the data resources with high time resolution. However, there are limitations and deficiencies in our study. On the one hand, this study only investigated the SOC loss but ignored the SOC input in a tidal salt marsh. In fact, it is crucial to considering the regulation of plants for revealing the mechanism of SOC loss (Duarte et al. 2013). On the other hand, microorganisms should be focused since they are play key role in the decomposition processes of SOC (Chambers et al. 2016). In the future, further studies need to be conducted on the mechanisms from the above two aspects.

The results of our study suggest that whether the frequency of soil drying-rewetting cycle increase or decrease, the carbon loss processes in tidal salt marsh would be severely disrupted. Based on present studies, the ability of salt marshes to build up

Fig. 5 Correlations of the cumulative CO_2 and CH_4 from each treatment with soil gravimetric water content and soil salinity during the 60-d incubations. Points were calculated as average values. Error bars represent standard deviation of replicates

(a) $y = -0.3x^2 + 13.24x - 8.44$
$r^2 = 0.95, p = 0.05$

(b) $y = 2x + 98.27$
$r^2 = 0.83, p = 0.03$

(c) $y = 0.59x^2 - 23.87x + 435.44$
$r^2 = 0.98, p = 0.02$

(d) $y = -5.88x + 301.41$
$r^2 = 0.82, p = 0.03$

Cumulative CO_2 emissions (g CO_2 m^{-2})

Cumulative CH_4 emissions (mg CH_4 m^{-2})

Gravimetric water content (w/w%)

Salinity (%)

vertically by sediment accretion enable them to persist or even prosper with sea level rise (Schuerch et al. 2018; Kirwan and Megonigal 2013). In comparison, drying-rewetting process in tidal salt marshes is more strongly influenced by the building of anthropogenic infrastructure and invasion of exotic plants (Kirwan et al. 2016; Spencer et al. 2016). On the one hand, anthropogenic barriers (such as coastal flood protection structures and coastal roads) completely obstructed the tidal inundation and made large area of tidal salt marsh transferred into dry land (Schuerch et al. 2018). On the other hand, the great capacity of exotic invasion plants for mitigating erosion and trapping sediment will also lead to a sharp decrease of drying-rewetting frequency in tidal salt marshes (Zuo et al. 2012). Their induced ecological imbalance even loss of tidal salt marsh ecosystems is going to accelerate soil organic carbon loss. Thus, it is critical in keeping the stability and healthy of the tidal salt marsh ecosystems for achieving emission mitigation and sink enhancement of soil organic carbon through careful nature-based adaptation solutions.

Conclusions

Tidal salt marsh, a type of "blue carbon" sinks, plays a crucial part in global carbon sequestration. However, this important carbon pool is endangered by a series of natural or human disturbances, which will change the tidal actions as well as the drying-rewetting frequencies. On the whole, our findings suggested that the decrease in drying-rewetting frequency will increase the loss of SOC, which may convert tidal salt marsh from carbon sinks into carbon sources. To be specific, less frequent drying-rewetting cycles followed by more CO_2 and less CH_4 emissions in tidal salt marshes. Soil moisture, in a certain range, negatively affects CO_2 emissions and positively affects CH_4 emissions. Besides, soil lateral carbon loss was also significantly impacted by drying-rewetting frequency, as tidal salt marshes soil with high drying-rewetting frequency has high potential of DOC loss. According to our results, we suggested that the management should take adequate nature-based actions to ensure the stability and healthy of tidal salt marshes, thus reducing the soil organic carbon loss. Moreover, there is a significantly positive correlation between soil DOC concentration and CO_2 emission rates. In the future, the effects of changes in drying-rewetting frequency on soil microbes in tidal salt marshes must be considered. Furthermore, it was found that vertical distribution of soil moisture and salt was being changed during drying-rewetting processes. Thus, future studies should also consider the effects of vertical migration of soil moisture and salinity on SOC decomposition during drying-rewetting processes.

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