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Diel methane emissions in stands of *Spartina alterniflora* and *Suaeda salsa* from a coastal salt marsh

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ABSTRACT

In this study, we aimed to understand the influence of plant type on the monthly variations of diel CH_4 fluxes from *Spartina alterniflora* and *Suaeda salsa* of coastal salt marshes at three growth stages (July, August and September). Dissolved CH_4 concentrations in porewater and sediment redox potentials were monitored, as were aboveground plant biomass and stem densities. CH_4 fluxes exhibited clear monthly variations and peaked in September in the *S. alterniflora* and *S. salsa* mesocosms. However, no discernible diel variation was observed in the CH_4 flux in the *S. salsa* mesocosm, probably due to its weak gas transport capacity. By contrast, notable diel variations of CH_4 flux with the peak of 1.42 and 3.67 mg CH_4 m^{-2} h^{-1} at 12:00 and the lowest of 0.75 and 2.11 mg CH_4 m^{-2} h^{-1} at 3:00 or 6:00 were observed in the *S. alterniflora* mesocosm on 11 August and 11 September, respectively, but not in July mainly due to low plant biomass masking diel variations in the porewater CH_4 concentration. The ratios of the maximum flux to minimum flux over the course of the day in the *S. alterniflora* mesocosm on 10 July, 11 August and 11 September were 1.28, 1.89 and 1.76, respectively, and corresponding values for porewater CH_4 concentration were 1.31, 1.39 and 1.17, respectively. CH_4 flux significantly correlated with CH_4 concentration in porewater, and both were significantly related to air temperature. These findings indicate that CH_4 production and CH_4 flux at the middle growth stage (August) exhibited greater responses to changes in air temperature, which in turn induced the higher diel variation. The higher diel cycle for CH_4 flux in August than in September was likely due to the higher proportion of CH_4 oxidized during diffusion within the aerenchyma system. Our results suggest that the extent of diel variations in CH_4 flux may have depended on the gas transport capacity of plants, and the highest diel variation occurred at the middle growth stage.

1. Introduction

From 1999 to 2006, the CH_4 concentration in the atmosphere remained at a stable level, but it has been showing a rising trend since 2007 (http://www.noaa.gov/). This increase is mainly attributed to increased CH_4 emissions from wetlands (Bloom et al., 2010). According to the Intergovernmental Panel on Climate Change (IPCC, 2007), annual CH_4 emissions from natural wetlands range between 100 and 231 T_g CH_4. However, this estimate is rather uncertain due to high spatial and temporal variations of CH_4 emissions in different kinds of wetlands where climate, vegetation and topography are remarkably diverse (Van der Nat and Middelburg, 2000; Cheng et al., 2007; Zhu et al., 2010). In the past decades, much attention has been focused on CH_4 emissions from freshwater wetlands (Ding et al., 2004; Rinne et al., 2007). However, there is little information available on CH_4 emissions from coastal salt marshes in China (Cheng et al., 2007; Zhang et al., 2010a), despite the fact that coastal wetland ecosystems display high potentials for carbon sequestration (Zhang et al., 2010b).

Spartina alterniflora, the Smooth Cordgrass species native to the Atlantic and Gulf coast marshes of North America that has a C_4 photosynthesis pathway, was intentionally introduced into the Chinese tidal coast to stabilize sediments in the 1970s (Qin and Zhong, 1992). At present it has replaced native species such as *Phragmites australis* and *Suaeda salsa* to become one of the dominant plants in the coast. Stohlgren et al. (2011) estimated that non-native species account for 13% of the most widely distributed vascular plant species in China, which cause a substantial threat to biodiversity and ecological integrity of native habitats and ecosystems, another global problem. Thus, variations among wetland plants can alter the activity of microorganisms associated with CH_4 production and oxidization and the rate of CH_4 released from wetlands to the atmosphere (Rinne et al., 2007; Long et al., 2010). Plants act as a source of methanogenic substrates by releasing exudates and providing root debris and respiratory CO_2 coupled to photosynthesis and as a source of oxygen stimulating CH_4 oxidation in the

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rhizosphere (Van der Nat and Middelburg, 2000; Laanbroek, 2010). The aerenchyma system in vascular plants can also provide a conduit for transport of CH_4 produced in anaerobic zones (Brix et al., 1992). However, different plants exhibit great differences in the quantities of carbohydrates and oxygen released by roots and in their capacities to transport gas (Bais et al., 2006; Laanbroek, 2010).

The diel variation of CH_4 emissions is widely correlated with abiotic and biotic factors such as temperature (Mikkela et al., 1995), irradiance (Whiting and Chanton, 1996), plant biomass and gas transport mechanisms (Kaki et al., 2001; Van der Nat et al., 1998). CH_4 can be released into the atmosphere through plants by diffusive transport and/or convective transport, depending on the plant type (Ding et al., 2004; Laanbroek, 2010). The diffusion rate of CH_4 after slowly passing through root cells and tissues may be facilitated by CH_4 concentration gradients between the sediment and atmosphere (Kaki et al., 2001). Garnet et al. (2005) suggested that CH_4 release from plants may be correlated with stomatal control, which can more or less induce diel variations (Nouchi et al., 1990; Wang and Han, 2005). The CH_4 emission rate from plants by diffusion is rather slow compared with that by bulk flow; the latter is mediated by pressure differences from the roots to the shoots and can result in significant diel variations in CH_4 emissions. This pressure gradient is generated in different plant parts relative to leaf temperature and humidity discrepancies that are driven by diurnal fluctuation in solar radiation (Brix et al., 1992; Long et al., 2010). Whiting and Chanton (1996) and Kaki et al. (2001) found that *P. australis* transports CH_4 by the diffusive mechanism in the dark and an additional convective mechanism under light conditions, resulting in large diel variations. When the less efficient diffusive transport is employed, CH_4 accumulates within aerenchyma tissues resulting in increased CH_4 concentrations, whereas it is efficiently flushed out in daylight when the more efficient convective flow is in use. Kohl et al. (1996) observed that the resistance to convective gas-flow is low during the summer but increases later during the growing season. This finding indicates that diel variations in CH_4 emissions from wetlands may change along with plant growth. To our knowledge, few studies have investigated monthly variations in the diel fluctuation of CH_4 emissions from wetlands.

In the present study, we designed a mesocosm experiment to monitor monthly variations of diel CH_4 emissions from *S. alterniflora* and *S. salsa* of the coastal wetlands at three growth stages. The objectives of this study were to (1) understand the monthly variations of diel fluctuations in CH_4 fluxes and (2) evaluate the effect of major environmental variables on diel CH_4 variations.

2. Materials and methods

2.1. Experimental design

The outdoor mesocosm experiment was conducted in the Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China (32°07′N, 118°50′E). We constructed the circular polyvinyl chloride (PVC) mesocosm with a 40-cm height and 25-cm inner diameter. Plants and soil were collected from the coastal salt marsh in Wanggang, Dafeng city, Jiangsu province, China (33°12′N, 120°47′E). In April 2009, the intact soil columns (30-cm depth and 25-cm diameter) collected using a specially designed stainless steel sampler were put into the mesocosms and transported to the experimental site in Nanjing. Soil for *S. alterniflora* contained 4.90 g organic C kg^{-1} and 0.391 g N kg^{-1}, whereas that for *S. salsa* contained 2.89 g organic C kg^{-1} and 0.252 g N kg^{-1}.

The experiment included two treatments: *S. alterniflora* and *S. salsa*. Three replicates of each treatment were laid out in a randomized block design, and all mesocosms were buried into the field at a depth of 30 cm. Plants of approximately equal size with five true leaves each were selected, and each mesocosm was planted with one young ramet of *S. alterniflora* or *S. salsa*. A rain-diversion system was constructed over the experimental site and was opened on sunny days and closed on rainy days. To simulate typical habitats in intertidal wetland ecosystems, soil in the mesocosms was subjected to a cycle of flooding and drying. The 5-cm depth of saltwater in each mesocosm was maintained for 24 h by adding saltwater sampled from the Wanggang estuary, after which it was removed by siphoning, and the soil was allowed to dry for 24 h. Saltwater collected in each mesocosm was kept in a sealed container for use in the next wet–dry cycle. During the experimental period, water salinity was maintained at approximately 5‰.

2.2. CH_4 flux measurements

To collect gas samples, a clear, open-bottom Plexiglass cylindrical chamber of 100-cm height and 27-cm diameter was placed on the mescosom by inserting the flange of the chamber into a water trough at the upper end of the mesocosm. An internal battery-operated fan was installed to provide air mixing. The chamber was equipped with two ports: a small, silicone-sealed vent for sampling and a second port for measuring chamber temperature. Each time, four gas samples from the chamber air were manually extracted into 50-mL syringes at 0, 10, 20 and 30 min after enclosure, injected into pre-evacuated vials and returned to the laboratory for analysis. The air temperature inside the chamber was simultaneously measured with a mercury thermometer. We selected sunny days, which generally accounts for 60–70% of the growing season, to monitor the diel variations of CH_4 emissions from *S. alterniflora* and *S. salsa* mesocosms on 10 July, 11 August and 11 September. Samplings were carried out at 3-h intervals, i.e., at 3:00, 6:00, 9:00, 12:00, 15:00, 18:00, 21:00 and 24:00 in Beijing standard time (GMT + 8 h). CH_4 concentrations were determined by gas chromatography on a Shimadzu GC12A instrument with a flame ionization detector (FID) and a 2-m Porapak Q (80/100 mesh) column. The rate of CH_4 increase in the chamber air was calculated from a linear regression of concentration versus time, using the chamber air temperature and atmospheric pressure. Coefficients of determination (R^2) for all linear regressions were greater than 0.95.

2.3. Measurements of porewater CH_4 concentrations

A Rhizon SMS-MOM soil porewater sampler (Eijkelkamp Agrisearch Equipment, Giesbeek, Netherlands) was used to collect CH_4 in interstitial water. The sampler consisted of a 5-cm long microporous polymer tube (2.5 mm outer diameter, 1.5 mm inner diameter) and a 30-cm PVC tube (2.7 mm outer diameter, 1.0 mm inner diameter). It was permanently installed at a depth of 5 cm in the soil before plants were transplanted. Soil porewater was collected immediately after CH_4 measurements. Prior to collecting samples, approximately 5 mL of porewater were extracted and discarded. A 20-mL pre-evacuated vial, filled with pure N_2 gas at 0.5 atm, was then connected to the sampler using a two-headed needle. Under the pressure strength, approximately 10 mL of porewater were drawn into the vial where the pressure ultimately reached 1.0 atm. The vials were stored in a cooling box (4 °C) in the field and immediately transported to our laboratory for analysis. To determine dissolved CH_4 concentrations, the vials were vigorously shaken for 5 min to degas the water. Gas samples were taken from the vial headspace and analyzed as described above. The amount of soil porewater collected and the headspace volume were determined by weighing the vials before and after sampling. CH_4