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Fluxes of nitrous oxide and methane in different coastal *Suaeda salsa* marshes of the Yellow River estuary, China

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HIGHLIGHTS

- ► Fluxes of N_2O and CH_4 in coastal marsh had different spatial and temporal variations.
- ► Coastal marsh represented N_2O emission and CH_4 sink during sampling campaigns.
- ► N_2O comprised the principal part of total CO_2-e emissions during spring and winter.
- ► Contributions of CH_4 to total CO_2-e could not be ignored during summer and autumn.

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ABSTRACT

The spatial and temporal variations of the fluxes of nitrous oxide (N_2O) and methane (CH_4) and associated abiotic sediment parameters were quantified for the first time across the coastal marsh dominated by *Suaeda salsa* in the Yellow River estuary during 2009/2010. During all times of day and the seasons measured, N_2O and CH_4 fluxes from coastal marsh ranged from -0.0147 mgN_2O m^{-2} h^{-1} to 0.0982 mgN_2O m^{-2} h^{-1} and -0.7421 mgCH_4 m^{-2} h^{-1} to 0.4242 mgCH_4 m^{-2} h^{-1}, respectively. The mean N_2O fluxes in spring, summer, autumn and winter were 0.0325 mgN_2O m^{-2} h^{-1}, 0.0089 mgN_2O m^{-2} h^{-1}, 0.0119 mgN_2O m^{-2} h^{-1} and 0.0140 mgN_2O m^{-2} h^{-1}, and the average CH_4 fluxes were -0.0109 mgCH_4 m^{-2} h^{-1}, -0.0174 mgCH_4 m^{-2} h^{-1}, -0.0141 mgCH_4 m^{-2} h^{-1} and -0.0089 mgCH_4 m^{-2} h^{-1}, respectively, indicating that the coastal marsh acted as N_2O source and CH_4 sink. Both N_2O and CH_4 fluxes differed significantly between times of day of sampling. N_2O fluxes differed significantly between sampling seasons as well as between sampling positions, while CH_4 fluxes had no significant differences between seasons or positions. Temporal variations of N_2O emissions were probably related to the effects of vegetation (*S. salsa*) during summer and autumn and the frequent freeze/thaw cycle of sediment during spring and winter, while those of CH_4 fluxes were controlled by the interactions of thermal conditions and other abiotic factors (soil moisture and salinity). Spatial variations of N_2O and CH_4 fluxes were primarily affected by soil moisture fluctuation derived from astronomic tide, sediment substrate and vegetation composition. N_2O and CH_4 fluxes, expressed as CO_2-equivaltent (CO_2-e) emissions, showed that N_2O comprised the principal part of total calculated CO_2-e emissions during spring and winter, while the contributions of CH_4 could not be ignored during summer and autumn. This study highlights the importance of seasonal N_2O and CH_4 contributions, particularly during times of significant CH_4 consumption. For the accurate up-scaling of N_2O and CH_4 fluxes to annual rates, a careful sampling design at site-level is required to capture the potentially considerable temporal and spatial variations of N_2O and CH_4 emissions.

1. Introduction

Nitrous oxide (N_2O) and methane (CH_4) are key radiatively active greenhouse trace gases which have been recognized to contribute global warming by 5% and 25%, respectively (Mosier, 1998). Quantification of the trace gases is a subject of great interest because accurate information is required to determine the contribution of these gases to global greenhouse gas fluxes (Khalil et al., 2002). IPCC (2007) has reported increased concentrations in N_2O and CH_4 since industrial times, a concern since both gases, although present in lower concentrations to that of carbon dioxide (CO_2), have 298 (N_2O) and 25 (CH_4) times the global warming potential of CO_2 over a 100-year time period. The current global

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atmospheric N_2O and CH_4 concentrations are 319 ± 0.12 ppb and 1774.62 ± 1.22 ppb, respectively, and are increasing approximately 0.26% and 1.1% per year (IPCC, 2007).

Emission of N_2O and CH_4 from various natural ecosystems has significant influences on the global climate change since they account for 44–54% of the total N_2O emissions and 30–40% of the total CH_4 emissions, respectively (IPCC, 2007). Tropical soil and wetlands play an important role in the global carbon (C) and nitrogen (N) biogeochemical cycles, and are considered significant natural sources of N_2O and CH_4, contributing approximately 22–27% (N_2O) and 24% (CH_4), respectively, towards this inventory (Whalen, 2005). Coastal marsh ecosystem is characterized by high temporal and spatial variations involved with topographic feature, environmental factors and astronomic tidal fluctuation, and is very sensitive to global climate changes and human activities. Above all, the intertidal zone between terrestrial and aquatic coastal ecosystems may represent a high dynamic interface of intense material processing and transport, with potentially high decomposition and associated greenhouse gases emission (Hirota et al., 2007). In the past two decades, considerable efforts have been made to quantify the N_2O and CH_4 fluxes in different coastal ecosystems, especially in estuarine salt marshes (Magalhães et al., 2007; Moseman-Valtierra et al., 2011), mangrove swamps (Allen et al., 2007; Ganguly et al., 2008), coastal lagoons (Gregorich et al., 2006; Hirota et al., 2007) and coastal marshes (Amouroux et al., 2002). In China, the studies on N_2O and CH_4 emissions from coastal marshes started quite late (in the 2000s), and the related research primarily focused on the coastal tundra marshes in Antarctica (Sun et al., 2002; Zhu et al., 2008) and the salt marshes in the Yangtze River estuary (Yang et al., 2006; Wang et al., 2007) and Min River estuary (Zeng et al., 2010; Mou et al., 2012). However, information on the coastal marshes in other estuaries is still very scarce.

The Yellow River is well known as a sediment-laden river. Every year, approximately 1.05×10^7 tons of sediment is carried to the estuary and deposited in the slow flowing landform, resulting in vast floodplain and special marsh landscape (Cui et al., 2009). Sediment deposition is an important process for the formation and development of coastal marshes in the Yellow River Delta. The deposition rate of sediment in the Yellow River not only affects the formation rate of coastal marsh, but also, to some extent, influences water or salinity status and plants succession. Coastal marsh is the main marsh type, with an area of 964.8 km^2, accounting for 63.06% of total area of the Yellow River Delta (Cui et al., 2009). *Suaeda salsa*, an annual C_3 plant, is one of the most prevalent halophytes in the coastal marshes of the Yellow River estuary. As a pioneer plant, it has strong adaptations to environmental stresses, such as high salinity, flooding and sediment burial (Han et al., 2005). *S. salsa* generally germinates in late April, blooms in July, matures in late September and completely dies in late November. In the intertidal zone, three phenotypes are formed due to the differences of water and salinity in high marsh, middle marsh and low marsh. In recent years, the N and organic matter loadings of the Yellow River estuary have significantly increased due to the effects of human activities, and approximately 4650 tons of nutrient and 4.33×10^5 tons of organic matter are discharged into Bohai Sea every year (Ocean Environmental Quality Communique of Shandong Province, 2009). Increases in N and organic matter loadings to estuarine and coastal environment can stimulate microbial processes and associated trace gases emission (Seitzinger and Kroeze, 1998). However, emissions of N_2O and CH_4 from different coastal *S. salsa* marshes in the Yellow River estuary remains poorly documented till now. In addition, because microbial processes affecting trace gas production are regulated by many parameters including oxygen availability, temperature, water content, sediment redox potential, salinity, pH and microbially available C and N sources (Bauza et al., 2002; Whalen, 2005), evaluating the influences of different environmental factors on the emissions of N_2O and CH_4 from coastal marsh will be of importance.

In this paper, we measured the N_2O and CH_4 fluxes from the intertidal zone of the Yellow River estuary using the closed chamber technique. The aims of this study are: (i) to quantify and compare the N_2O and CH_4 fluxes from different coastal *S. salsa* marshes and bare flat; (ii) to determine whether distinct spatial and temporal variation occurs in N_2O and CH_4 flux throughout the day and in different seasons; (iii) to examine how environmental factors influence N_2O and CH_4 emissions.

2. Materials and methods

2.1. Site description

The study was carried out in the intertidal zone of the Yellow River estuary, which is located in the Nature Reserve of Yellow River Delta (37°35′N–38°12′N, 118°33′E–119°20′E) in Dongying City, Shandong Province, China. The nature reserve is of typical continental monsoon climate with distinctive seasons. The temperature changes significantly during early spring and winter, and the freeze/thaw cycles frequently occur in topsoil in majority days, with the frozen depth ranged from 0 cm to 15 cm. The annual average temperature is 12.1 °C, and the frost-free period is 196 d. The average temperature in spring, summer, autumn and winter are 10.7 °C, 27.3 °C, 13.1 °C and -5.2 °C, respectively. The annual evaporation is 1962 mm; the annual precipitation is 551.6 mm, and about 70% of precipitation occurring between June and August. The soils are dominated by intrazonal tide soil and salt soil and the main vegetation types include *Phragmites australis*, *S. salsa*, *Triarrhena sacchariflora*, *Tamarix chinensis* and *Imperata cylindrica*.

Intertidal zone sediment is composed mainly of fine particles. Natural geomorphology and depositing zones are distinct. High marsh, middle marsh, and low marsh develop from the land to the sea. The high marsh is predominated by *S. salsa* (>90%) and *P. australis* (<10%), while middle marsh is predominated by *S. salsa* (>95%) and *T. chinensis* (<5%). Low marsh includes two distinct ecosystem-types. One is pure *S. salsa* community (100%), with sparse distribution in the intertidal zone, and the other is bare flat. The coverage and maximum aboveground biomass of *S. salsa–P. australis*, *S. salsa–T. chinensis* and *S. salsa* communities are 95%, 80%, 60% and 902.08 ± 195.81 g m^{-2}, 564.89 ± 99.66 g m^{-2}, 252.97 ± 29.24 g m^{-2}, respectively. In this study, four typical sampling positions were laid in high *S. salsa* marsh (HSM), middle *S. salsa* marsh (MSM), low *S. salsa* marsh (LSM) and bare flat (BF) on the northern coastal marsh of the Yellow River estuary. The initial physical and chemical properties of topsoil (0–10 cm) in the four positions are shown in Table 1.

2.2. Experimental design

Fluxes of N_2O and CH_4 were measured by using static, manual stainless steel chambers and gas chromatography techniques. The chamber is an open-bottom a square box (50 cm × 50 cm × 50 cm) and equipped with an electric fan installed on the top wall of each chamber to make turbulence when chamber was closed. Outside of the chamber was covered with 2 cm thickness white foam to reduce the impact of direct radiative heating during sampling. In August 2009, the stainless steel base (50 cm × 50 cm × 20 cm) with a water groove on top was installed at the four sampling positions. During observations, the chamber was placed over the base filled with water in the groove to ensure air-tightness, and the plant was covered within the chamber.

Sampling campaigns were undertaken during four seasons in October 2009 (autumn), December 2009 (winter), April 2010