Responses of CH₄ Emissions to Nitrogen Addition and *Spartina alterniflora* Invasion in Minjiang River Estuary, Southeast of China

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Abstract: The nitrogen (N) input and *Spartina alterniflora* invasion in the tidal marsh of the southeast of China are increasingly serious. To evaluate CH₄ emissions in the tidal marsh as affected by the N inputs and *S. alterniflora* invasion, we measured CH₄ emissions from plots with vegetated *S. alterniflora* and native *Cyperus malaccensis*, and fertilized with exogenous N at the rate of 0 (N0), 21 (N1) and 42 (N2) g N/(m²·yr), respectively, in the Shanyutan marsh in the Minjiang River estuary, the southeast of China. The average CH₄ fluxes during the experiment in the *C. malaccensis* and *S. alterniflora* plots without N addition were 3.67 mg CH₄/(m²·h) and 7.79 mg CH₄/(m²·h), respectively, suggesting that the invasion of *S. alterniflora* into the Minjiang River estuary stimulated CH₄ emission. Exogenous N had positive effects on CH₄ fluxes both in native and in invaded tidal marsh. The mean CH₄ fluxes of N1 and N2 treatments increased by 31.05% and 123.50% in the *C. malaccensis* marsh, and 63.88% and 7.55% in the *S. alterniflora* marsh, respectively, compared to that of N0 treatment. The CH₄ fluxes in the two marshes were positively correlated with temperature and pH, and negatively correlated with electrical conductivity and redox potential (Eh) at different N addition treatments. While the relationships between CH₄ fluxes and environmental variables (especially soil temperature, pH and Eh at different depths) tended to decrease with N additions. Significant temporal variability in CH₄ fluxes were observed as the N was gradually added to the native and invaded marshes. In order to better assess the global climatic role of tidal marshes as affected by N addition, much more attention should be paid to the short-term temporal variability in CH₄ emission.

Keywords: nitrogen addition; CH₄ emission; tidal marsh; *Spartina alterniflora* invasion; temporal variability

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1 Introduction

Human activities, primarily fertilizer application, fossil fuel combustion, land use change and development of industry and stock raising, have drastically increased the inputs of nitrogen (N) to stimulate plant growth, change species composition and diversity, and alter carbon (C) and N cycling rate in most ecosystems since the indus-

trial revolution (Matson *et al.*, 2002). Increasing N loading can thus affect the structure and function of ecosystems (Matson *et al.*, 2002; Fang *et al.*, 2012). High N input by human activities is of concern because it may alter the emission of greenhouse gases to the atmosphere and further contribute to global warming (Dalal and Allen, 2008; Liu and Greaver, 2009).

CH₄ is one of the important greenhouse gases con-

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tributing to global warming, and human activities have dramatically increased its concentrations by 48% since pre-industrial times (IPCC, 2007). Although wetlands only cover 4%–6% of the Earth land surface (Matthews and Fung, 1987; Aselmann and Crutzen, 1989), they store more than one third of the global terrestrial C and serve as a net C sink due to low decomposition (Gorham, 1991). Estuarine intertidal zones represent the interface between terrestrial and marine ecosystems, which are sensitive to global climate change and human activities (Mou *et al.*, 2011). In the estuarine tidal marsh, N deposition, N produced by agricultural and industrial activities and N directly imported by the river can contribute to the total N inputs of the marsh. The tidal marshes are highly productive coastal wetlands, which can provide many important ecosystem services, such as storm protection for coastal cities, nutrient removal and carbon sequestration (Deegan *et al.*, 2012). Increasing N loading may have strong effects on CH₄ emissions from the estuarine environments by influencing plant growth (Zhang *et al.*, 2010), changing the biological and chemical properties of soils (Min *et al.*, 2011), stimulating the microbial processes (Blagodatskaya *et al.*, 2007; Inselsbacher *et al.*, 2011). Zhang *et al.* (2010) studied the CH₄ emissions in the Wanggang coastal marsh and found that exogenous N addition dramatically stimulated CH₄ emission from the *Spartina alterniflora* mesocosm, and the effect of N addition on CH₄ emission from the native *Suaeda salsa* mesocosm was not significant. Moseman-Valtierra *et al.* (2011) reported that CH₄ fluxes were not significantly affected by nitrate addition in the coastal marsh. But there is little known available data about the CH₄ emission response to N additions in natural sub-tropical estuarine tidal marshes, such as those in the Minjiang River estuary, the southeast of China.

The tidal marshes in the Minjiang River estuary are typical marshes in the subtropical zone of China, which are dominated by the native *Cyperus malaccensis*, *Phragmites australis* and the alien invasive *S. alterniflora*. *S. alterniflora* was intentionally introduced to China for the purposes of erosion control and sediment accretion in 1979 (Chung, 1993), but it had become highly invasive in many coastal wetlands in China (Jiang *et al.*, 2009). *S. alterniflora* began to invade the Minjiang River estuary since 2002, and currently it was a dominant species in this area. Variations in plant

composition can alter the CH₄ emission from the wetlands to the atmosphere. Cheng *et al.* (2007) found that the CH₄ emission rates were higher in *S. alterniflora* mesocosm than those in native mesocosm due to its higher biomass and density, which could fix more available substrates to the soil and potentially emit more gases. Zhang *et al.* (2007) also reported that the *S. alterniflora* plants significantly stimulated CH₄ emission from wetland mainly because of higher plant biomass compared to native plants. According to the 'Report on the Status of the Marine Environment in Fujian in 2009', the Minjiang River estuary was seriously polluted by inorganic N and active phosphate (P), and approximately 19 927 t of N and P pollutants were imported into the sea by the Minjiang River. However, information on the effects of N loading on CH₄ emission from the native *C. malaccensis* marsh and the invaded *S. alterniflora* marsh in the Minjiang River estuary remains scarce.

The primary objectives of this study are: 1) to experimentally examine the effects of two levels of N addition and *S. alterniflora* invasion on CH₄ fluxes from the native and invaded marshes in the Minjiang River estuary; and 2) to measure the temporal variability of CH₄ fluxes and the relationships between CH₄ fluxes and environmental factors in response to N pulses.

2 Materials and Methods

2.1 Study area

This study was conducted in the Shanyutan marsh (26°00'36"–26°03'42"N, 119°34'12"–119°40'40"E), which is the largest tidal marsh with typical semi-diurnal tides in the Minjiang River estuary, the southeast of China. The local climate is warm and wet, with a mean annual temperature of 19.6°C and a mean annual precipitation of 1350 mm (Zheng *et al.*, 2006). The soils in the study area are dominated by coastal saline soil. The vegetation is dominated by *C. malaccensis*, *P. australis* and *Scirpus triqueter*. *C. malaccensis*, a perennial C₃ plant, is one of the most prevalent native halophytes in the Minjiang River estuary, which can tolerate coastal seawater salinity and salinity fluctuations resulting from water evaporation and tidal inundation. Local historical records showed that *S. alterniflora* began to invade the Shanyutan marsh in 2002 and expanded its cover from the lower intertidal zone to the upper intertidal zone in

2004. Currently, the situation of *S. alterniflora* invasion is increasingly serious and more than 50% of the area of the Shanyutan marsh has been covered by *S. alterniflora* (Zhang W L *et al.*, 2011).

2.2 Experimental design

A nitrogen addition experiment was conducted in the *C. malaccensis* marsh and *S. alterniflora* marsh of the Minjiang River estuary from April to June in 2011. In each marsh, nine plots (each with 1 m × 1 m dimension) were laid and three N input treatments (each treatment includes 3 replicates) were assigned randomly, with 18 plots in total. The N input include control (0 g N/(m²·yr), N0), low (21 g N/(m²·yr), N1) and high (42 g N/(m²·yr), N2) levels. The low N level approximated the current total N import amount (N deposition and N directly imported by the river) of the Minjiang River estuary (Huang *et al.*, 2005; Duan *et al.*, 2007; Liu *et al.*, 2013), while high N level was applied to study the CH₄ emission as high N saturated conditions occurring in the future (Zhang *et al.*, 2007). The N application was initiated at the onset of the experiment and continued throughout the CH₄ observation. Annual N import amount was divided into seven equal doses and applied every 8 days over a total time period of 56 days. On each application date, NH₄NO₃ was weighed, dissolved in 1 L surface marsh water, and applied to each plot by using a sprayer. The control plot received 1 L water without N.

2.3 Gas sampling

Fluxes of CH₄ were measured by using static, manual plexiglass chambers and gas chromatography techniques. The chamber is an open-bottom box and equipped with a fan installed on the top wall of each chamber to make turbulence when chamber is closed. The chambers covered an area of 35 cm × 35 cm, but the chamber height varied, depending on the height of plants, including 50 cm, 100 cm, 120 cm and 140 cm. In April 2011, a PVC base (35 cm in length, 35 cm in width and 50 cm in height) with a water groove on top was installed at each of the 18 plots. Gas samplings were undertaken in control and N addition plots after 3 hours of manipulations to test the effect of N input in a very short time. To test the persistence of N enrichment effects, gases were sampled again 8 days after the N addition. These measurements were repeated (3 hours and 8 days

after N addition) for each of the seven N additions. On each sampling time, 18 chambers were placed over the bases filled with water in the groove to ensure air-tightness and gas samples were taken simultaneously from the 18 plots over a 30 minutes period. About 60 mL gas sample inside the chamber was collected every 10 minutes over the 30 minutes period by using 100 mL plastic syringes (total of four samples), and then stored in 100 mL gas bags (Dalian Delin gas Packing Co., Ltd., China), which were inert to greenhouse gases and had been evacuated to -1.013×10^5 Pa in advance. CH₄ concentrations of gas samples were analyzed within 36 h by using gas chromatography (Agilent7890A, USA) equipped with an electron capture detector.

The gas flux was calculated according to the following equation (Song *et al.*, 2008):

$$J = \frac{dc}{dt} \times \frac{M}{V_0} \times \frac{P}{P_0} \times \frac{T_0}{T} \times H \quad (1)$$

where dc/dt is the slope of the gas concentration curve variation along with time. M is the mole mass of each gas. P is the atmospheric pressure in the sampling site. T is the absolute temperature during sampling. V_0 , T_0 , P_0 are the gas mole volume, air absolute temperature and atmospheric pressure under standard conditions, respectively. H is the height of chamber above the ground surface.

The rates of gas fluxes were calculated from the linear regression of change in the gas concentration over time. Only the samples with a regression determination coefficient R^2 higher than 0.95 were used for further analysis.

2.4 Environmental parameters measurement

Air temperature was measured by Kestrel-3500 (USA) in each vegetation group during gas sampling. Electrical conductivity (EC) at 0 cm, 5 cm and 10 cm depths in each plot were monitored after gas sampling using 2265FS Portable Conductivity Meter (IQ Scientific Instruments, USA), and ground temperature, pH and oxidation-reduction potential (Eh) at 0 cm, 5 cm and 10 cm depths were determined using IQ150 Portable pH/Eh/Thermometer (Spectrum Technologies Inc, USA).

2.5 Statistical analyses

The results were presented as means of the replications, with standard error (SE). Figures were drawn by Origin 7.5 software, while statistical analyses were carried out

with SPSS 13.0. The effects of N addition and *S. alterniflora* invasion on CH₄ fluxes were analyzed by one-way analysis of variance (ANOVA) in the treatments. Correlation analyses and linear regression models were used to examine the relationships between gas fluxes and environmental variables. For all tests, differences were considered significant only if $p < 0.05$.

3 Results

3.1 Response of CH₄ emission to *S. alterniflora* invasion

The background CH₄ fluxes from the native *C. malaccensis* marsh showed significant temporal variability ($p < 0.001$) (Fig. 1) and the mean coefficient of variations was 55.14%. The magnitudes of CH₄ fluxes in the *C. malaccensis* marsh was in a range of 0.16 mg CH₄/(m²·h) to 8.59 mg CH₄/(m²·h) and averaging 3.67 mg CH₄/(m²·h), indicating that the *C. malaccensis* marsh act as CH₄ source in the growing season.

The invasion of *S. alterniflora* significantly increased CH₄ fluxes during the experiment ($p < 0.01$) (Fig. 1). In the *S. alterniflora* marsh, the CH₄ fluxes ranged from 2.02 mg CH₄/(m²·h) to 18.42 mg CH₄/(m²·h) and the mean value was 7.79 mg CH₄/(m²·h), increased by 112.26% compared to the *C. malaccensis* marsh. The mean coefficient of variation of CH₄ fluxes in the *S. alterniflora* marsh was 62.06% which was higher than that in the *C. malaccensis* marsh.

Fig. 1 CH₄ fluxes from *C. malaccensis* and *S. alterniflora* marshes. Error bars indicate standard errors ($n = 3$) of mean, and 3 in brackets at the X axis indicates 3 hours after nitrogen addition. In other figures, it indicates the same meaning

3.2 Overall responses of CH₄ flux to N additions

Over all sampling periods, CH₄ fluxes were not significantly affected by N additions ($p > 0.05$) both in *C. malaccensis* marsh and in *S. alterniflora* marsh (Fig. 2). In the *C. malaccensis* marsh, the mean CH₄ fluxes of N addition treatments were 4.81 mg CH₄/(m²·h) (N1) and 8.20 mg CH₄/(m²·h) (N2), increased by 31.05% and 123.50%, respectively, compared to N0 treatment. Comparatively, the mean CH₄ fluxes of N addition plots in the *S. alterniflora* marsh were 12.77 mg CH₄/(m²·h) (N1) and 8.38 mg CH₄/(m²·h) (N2), compared to N0

Fig. 2 CH₄ fluxes from *C. malaccensis* and *S. alterniflora* marshes as affected by increasing nitrogen input. Error bars indicate standard errors ($n = 3$) of mean

treatment, increased by 63.88% and 7.55%, respectively.

3.3 Temporal variability of CH₄ flux in response to N additions

After 3 h of N addition, CH₄ fluxes from *C. malaccensis* marsh were significantly affected by N addition ($p < 0.01$) (Figs. 2 and 3). Significantly higher CH₄ fluxes were observed in the N2 treatment compared to N0 and N1 treatments ($p < 0.01$). The mean CH₄ fluxes decreased by 7.98% in the N1 treatment and increased by 141.78% in the N2 treatment (Fig. 3). After 8 days, significant differences still existed between N2 and N0 treatments ($p < 0.05$). Compared to N0 treatment, the mean CH₄ fluxes in the N1 and N2 treatments increased by 65.86% and 107.41%, respectively.

In the *S. alterniflora* marsh, CH₄ fluxes were not significantly affected by N addition after 3 h of N addition ($p > 0.05$) (Figs. 2 and 3), and the mean values of N addition treatments increased by 50.92% (N1) and 4.08% (N2), respectively. After 8 days, CH₄ fluxes were significantly affected by N addition ($p < 0.05$), and the mean values increased by 72.25% (N1) and 9.04% (N2), respectively (Fig. 3).

3.4 Relationships between CH₄ fluxes and environmental variables

The CH₄ fluxes from the two marshes were positively correlated with temperature and pH, and negatively correlated with EC and Eh at different N addition treatments (Figs. 4, 5, 6 and 7). At N0 treatment, the correlations were significant between CH₄ fluxes and soil tem-

perature, pH and Eh at different depths, and between CH₄ fluxes and EC at 0 cm and 5 cm soil depths in the two marshes ($p < 0.05$). Also, significant correlation was observed between CH₄ fluxes and air temperature in the *S. alterniflora* marsh. However, the correlation coefficients between CH₄ fluxes and environmental variables tended to decrease with N additions as the pair sample sizes were equal (Figs. 4, 5, 6 and 7), indicating that the relationships, especially those between CH₄ fluxes and soil temperature, pH and Eh at different depths, tended to decrease with N additions. At N1 treatment, significant correlations were found between CH₄ fluxes and soil temperature in 0 cm and 5 cm, soil EC at 0 cm, pH and Eh in three depths in the *C. malaccensis* marsh, and between CH₄ fluxes and soil EC of 0 cm and 5 cm, soil pH and Eh at 0 cm in the *S. alterniflora* marsh. While at N2 treatment, the significant correlations were only observed between CH₄ fluxes and soil EC of 0 cm and 5 cm in the *C. malaccensis* marsh, and soil EC at 0 cm in the *S. alterniflora* marsh.

4 Discussion

4.1 Effects of *S. alterniflora* invasion and exogenous N addition on CH₄ emission

In this study, we compared the CH₄ fluxes from invasive *S. alterniflora* marsh and native *C. malaccensis* marsh and found that the CH₄ emission from the former were significantly higher than those from the latter, indicating that the invasion of *S. alterniflora* into the Minjiang River estuary stimulated CH₄ emission to the at-

Fig. 3 Mean CH₄ fluxes from *C. malaccensis* and *S. alterniflora* marshes after 3 hours and 8 days of nitrogen addition. Values with the same superscript letters are not significantly different at $p < 0.05$ according to Turkey's test. Error bars indicate standard errors of mean ($n = 7$)

Fig. 4 Relationships between CH₄ fluxes and air temperature and soil temperature in *C. malaccensis* and *S. alterniflora* marshes

mosphere. This result is consistent with the conclusions of Cheng *et al.* (2007) and Zhang *et al.* (2010) who observed more CH₄ emissions from the invasive *S. alterniflora* marsh than those from the native marshes. The results of many studies showed that plant species are important drivers of CH₄ emission in wetland ecosystems (Whiting and Chanton, 1993; Ding *et al.*, 2005; Kao-kniffin *et al.*, 2010). Kao-kniffin *et al.* (2010) found that plant functional groups and plant biomass were useful indicators of CH₄ flux difference across plant species. Cheng *et al.* (2007) reported that the CH₄ fluxes in invasive *S. alterniflora* marsh were higher

than those in the native *P. australis* marsh due to its significantly higher biomass and density, which could fix more available substrates to the soil and potentially emit more CH₄. Plants can have significant effect on the emission of CH₄ from wetland ecosystems by altering its production, consumption and transport in the soil (Whiting and Chanton, 1993; Christensen *et al.*, 2003; Saarnio *et al.*, 2004; Koelbener *et al.*, 2010). Huang (2010) reported that the CH₄ transport capacity of *S. alterniflora* was obviously higher than that of *C. malaccensis* due to the bigger size of plant and medullary cavity. However, how the *S. alterniflora* invasion af-

Fig. 5 Relationships between CH₄ fluxes and EC at different soil depths in *C. malaccensis* and *S. alterniflora* marshes

fects CH₄ production and consumption in the tidal marshes of the Minjiang River estuary needs to be further studied.

The N addition has been recognized to strongly affect CH₄ emissions from wetland ecosystems. In this study, we found that the mean CH₄ fluxes increased by 31.05% (N1) and 123.50% (N2) in the *C. malaccensis* marsh, and 63.88% (N1) and 7.55% (N2) in the *S. alterniflora* marsh with the rates of 21 g NH₄NO₃-N/m² and 42 g NH₄NO₃-N/m² addition during the experiment, suggesting that the increased input of N to tidal

marshes would increase the contribution of CH₄ to the atmosphere. Similar results were drawn by other studies. Zhang *et al.* (2007) observed that the application of NH₄NO₃ with the rates of 6 g N/m², 12 g N/m² and 24 g N/m² increased CH₄ emission by 181%, 254% and 155%, respectively, in a freshwater marsh in the Sanjiang Plain of China. Zhang *et al.* (2010) suggested that N addition significantly increased CH₄ emissions from *S. alterniflora* and *S. salsa* marshes. We considered that the differences of plant species and biomass, amount and forms of added N, substrate properties and obser-

Fig. 6 Relationships between CH₄ fluxes and pH at different soil depths in *C. malaccensis* and *S. alterniflora* marshes

Fig. 7 Relationships between CH_4 fluxes and Eh at different soil depths in *C. malaccensis* and *S. alterniflora* marshes

vation time after N addition might explain the differences in CH_4 emissions between ecosystems. The results of this study also indicated that, in the N1 treatment, the N addition significantly stimulated CH_4 emission in the invasive *S. alterniflora* marsh rather than in the native *C. malaccensis* marsh, which was consistent with the results of Zhang *et al.* (2010). While in the N2 treatment, the increase of CH_4 emission in *S. alterniflora* marsh was lower than that in *C. malaccensis* marshes, and the probable reason might be the excess N imported

into the ecosystems inhibited the activities of microbe in *S. alterniflora* marsh.

4.2 Temporal variability in CH_4 emission

Temporal dynamics in greenhouse gas fluxes are likely to be particularly great in estuarine marsh ecosystems which have dynamic landscapes (Moseman-Valtierra *et al.*, 2011). In this study, we found that CH_4 emissions showed significant temporal variability after the N was added to the marshes, indicating that the differences of

observation time after N addition would induce different experimental results. The related studies suggested that the input of available C and N sources might increase microbial activity in soil and induce priming effects, which were the short-term changes in soil organic matter decomposition after substrate addition (Blagodatskaya *et al.*, 2007; 2011). We thought that the temporal dynamics in gas fluxes were probably due to the temporally variable responses of plant, animal and microbe to exogenous N, and the digestion, transformation or accumulation of exogenous N in the ecosystem might vary over time. The results of previous studies showed that the temporal variability of ecological impacts of exogenous N was also closely related to the frequency of N addition, substrate conditions and environmental factors (Bradford *et al.*, 2001; Jiang *et al.*, 2010; Inselsbacher *et al.*, 2011). Therefore, in our opinion, the establishment of time-series models, based on CH₄ fluxes and N input levels, as well as variability of soil properties and environmental factors, would more accurately assess and predict the effect of N addition on CH₄ emission, and provide reliable data to the estimation of ecosystem greenhouse gas inventories.

4.3 Effects of environmental variables on CH₄ emission

Temperature is one of the major factors affecting the variation in CH₄ emission. Carter *et al.* (2011) reported that elevated temperature increased the CH₄ uptake in the temperate heathland because of reduced soil moisture. Jiang *et al.* (2010) also found a significantly positive correlation between CH₄ uptake and air or soil temperature. While Danevcic *et al.* (2010) observed that CH₄ emissions in the Ljubljana marsh were not affected by soil temperature at 5 cm depth. In this study, the CH₄ emissions were positively related to air temperature or soil temperature in the two marshes, which was consistent with the results from Watanabe *et al.* (2005) who found that there was significant positive correlation between total CH₄ emission throughout the rice growth period and sum of effective temperature. Tong *et al.* (2010) reported that the estimated air Q₁₀ values of CH₄ emission ranged from 2.89 to 7.78, and soil Q₁₀ values from 3.22 to 11.10 in the Minjiang River estuary marshes, indicating that CH₄ emissions in the tidal marshes were sensitive to the changes of temperature.

Soil salinity is one of the important factors affecting

soil microbial activities and CH₄ emissions in coastal zone (Zhang J *et al.*, 2011). In this study, the CH₄ emissions were negatively related to soil EC at different depths in the two marshes. Similar results were drawn by other studies. The results of Datta *et al.* (2013) showed that the increased soil salinity decreased CH₄ emission during the dry season in a coastal saline rice field. Zhang J *et al.* (2011) reported that salt addition did not significantly affect the CH₄ uptake in the saline soils, indicating that the CH₄ oxidizers had higher tolerance to salt in the saline soil. The results of this study also indicated that the CH₄ emissions at N₀ treatment were significantly related to soil EC at 0 cm and 5 cm depths in the two marshes, while the correlations between CH₄ emissions and 10 cm soil EC were not significant, suggesting that the CH₄ emissions were more sensitive to the EC in topsoil.

Significant positive relationships between CH₄ fluxes and soil pH at different treatment were observed in this study, and similar results were reported by related researches. Ye *et al.* (2012) found that pH was a dominant control in differences of CH₄ production across sites, and higher pH enhanced CH₄ production and low pH inhibited CH₄ production mainly through direct inhibition of methanogenesis pathways. While Kato *et al.* (2011) revealed a significant negative relationship of CH₄ emissions with soil pH in the alpine wetland. There exists optimum pH for CH₄ production and oxidation. Saari *et al.* (2004) found that the optimum pH for CH₄ oxidation varied from 4.0 to 7.5 in forest soils. Singh *et al.* (2000) concluded that soil pH is an important factor affecting the CH₄ production because methanogenic bacteria are pH sensitive and grow at a relatively narrow pH range of 6–8. In the present study, the soil pH ranged from 5 to 8 in different treatments of the two marshes. Therefore, the soils were favorable for the optimum growth of methanogenic bacteria at different N addition treatment, suggesting that pH might not be responsible for the difference of CH₄ fluxes as affected by the N additions.

We also found that CH₄ emissions were negatively correlated with soil Eh at different depths in the two marshes, which was consistent with the results from Kato *et al.* (2011) who found that soil Eh had a remarkably strong influence on CH₄ emissions for nine chambers above the water level, resulting in a negative exponential relationship in the alpine wetland. Ding

et al. (2010) observed that inundation significantly reduced Eh in sediment, which increased the CH₄ emission in the *S. alterniflora* marsh. Singh (2001) considered that Eh was the most important edaphic factors affecting CH₄ emission and it greatly determined the action of methanogenic bacteria. Moreover, the Eh was negatively correlated with temperature or pH, and any change in soil temperature and pH might have direct effect on Eh (Singh, 2001). All those might largely determine the methanogenesis processes that were responsible for CH₄ emissions.

However, the relationships between CH₄ fluxes and environmental variables tended to decrease with N additions in this study. The probable reason may be that the added N instead of other environmental variables becomes an important factor affecting the CH₄ emission in the tidal marshes.

5 Conclusions

The CH₄ fluxes were observed in the early growing season in the native and invaded tidal marshes in the Minjiang River estuary. The results showed that the invasion of *S. alterniflora* stimulated CH₄ emission of the *C. malaccensis* marsh. And exogenous N addition increased the CH₄ emission both in native and in invaded tidal marshes. But how *S. alterniflora* invasion and N addition affects CH₄ production, consumption and transport in the Minjiang River estuarine wetland need to be further studied. In this study, we also found that the relationships between CH₄ fluxes and environmental variables tended to decrease with N additions. Probable reason may be that the added N instead of other environmental variables becomes an important factor affecting the CH₄ emission in the tidal marshes. And significant temporal variability of CH₄ fluxes were observed after the N was gradually added to the native and invaded marshes. Many studies demonstrated that longer study periods were needed to verify the cumulative effects of increasing N on greenhouse gas fluxes in ecosystems. However, we concluded that the increase of CH₄ emissions affected by N addition in coastal regions will be misestimated due to the short-term temporal variations of CH₄ fluxes after N addition. In order to better assess the global climatic role of salt marshes as affected by N addition, the short-term temporal variability of CH₄ emission also should be paid much more attention.

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