

1 **Factors influencing CO<sub>2</sub> and CH<sub>4</sub> emissions from coastal wetlands in the**  
2 **Liaohe Delta, Northeast China**

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10 **Abstract**

11 Many factors are known to influence greenhouse gas emissions from coastal wetlands, but it is still  
12 unclear which factors are most important under field conditions when they are all acting  
13 simultaneously. The objective of this study was to assess the effects of water table, salinity, soil  
14 temperature and vegetation on CH<sub>4</sub> emissions and ecosystem respiration (R<sub>eco</sub>) from five coastal  
15 wetlands in the Liaohe Delta, northeast China: Two *Phragmites australis* (common reed) wetlands,  
16 two *Suaeda salsa* (sea blite) marshes and a rice (*Oryza sativa*) paddy. Throughout the growing  
17 season, the *Suaeda* wetlands were net CH<sub>4</sub> sinks whereas the *Phragmites* wetlands and the rice  
18 paddy were net CH<sub>4</sub> sources emitting 1.2-6.1 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup>. The *Phragmites* wetlands emitted the  
19 most CH<sub>4</sub> per unit area and the most CH<sub>4</sub> relative to CO<sub>2</sub>. The main controlling factors for the CH<sub>4</sub>  
20 emissions were water table, temperature, soil organic carbon and salinity. The CH<sub>4</sub> emission was  
21 accelerated at high and constant (or managed) water tables and decreased at water tables below  
22 the soil surface. High temperatures enhanced CH<sub>4</sub> emissions, and emission rates were consistently  
23 low (<1 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup>) at soil temperatures <18°C. At salinity levels >18 ppt, the CH<sub>4</sub> emission  
24 rates were always low (<1 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup>) probably because methanogens were outcompeted by  
25 sulphate reducing bacteria. Saline *Phragmites* wetlands can, however, emit significant amounts of  
26 CH<sub>4</sub> as CH<sub>4</sub> produced in deep soil layers are transported through the air-space tissue of the plants  
27 to the atmosphere. The CH<sub>4</sub> emission from coastal wetlands can be reduced by creating  
28 fluctuating water tables, including water tables below the soil surface, as well as by occasional  
29 flooding by high-salinity water. The effects of water management schemes on the biological  
30 communities in the wetlands must, however, be carefully studied prior to the management in  
31 order to avoid undesirable effects on the wetland communities.

32 Keywords: Coastal wetlands, common reed, greenhouse gas emissions, *Phragmites australis*, rice  
33 paddy, seablite, *Suaeda salsa*

## 34 **1 Introduction**

35 Wetlands play an important role in the global carbon cycling as they function both as carbon sinks,  
36 by storing carbon in soils and vegetation, and as carbon sources, by releasing CO<sub>2</sub> and CH<sub>4</sub> into the  
37 atmosphere (Brix et al., 2001; Kayranli et al., 2010; Mitsch et al., 2013; Whiting and Chanton,  
38 2001). Carbon dioxide is fixed by plants and autotrophic microorganisms through photosynthesis  
39 and thereby transformed to organic compounds locked away from the atmosphere, a process  
40 called carbon sequestration (Kayranli et al., 2010). Wetlands can store organic carbon vectored  
41 into the soil for a long time due to the generally slow decomposition rates in anaerobic wetland  
42 soils (Mitsch et al., 2013). Decomposition of organic matter does however still take place, both  
43 through aerobic and anaerobic processes. Aerobic processes are more efficient and mainly form  
44 CO<sub>2</sub> as an end-product, whereas anaerobic decomposition is much slower and, along with CO<sub>2</sub>,  
45 also produces CH<sub>4</sub>. Both gases are known as greenhouse gases, which cause global warming due to  
46 their ability to absorb solar radiation (IPCC, 2007). The global warming potential (GWP) of CH<sub>4</sub> is 25  
47 times greater than that of CO<sub>2</sub> on a 100 year time scale (IPCC, 2007) and high emissions of CH<sub>4</sub> can  
48 therefore have disproportionately adverse effects on the climate. According to Whalen (2005),  
49 wetlands contribute to about 24% of global CH<sub>4</sub> emissions from all sources, and are the largest  
50 natural source of CH<sub>4</sub>. Due to the increasing concern of greenhouse gas emissions and global  
51 warming, it is important to gain more knowledge about the factors affecting CO<sub>2</sub> and CH<sub>4</sub>  
52 emissions in different wetland systems, and understand how the balance might be affected by  
53 management actions.

54 Previous work has shown that environmental factors like water table (Altor and Mitsch, 2008;  
55 Couwenberg et al., 2011; Hargreaves and Fowler, 1998), soil temperature (Bridgham and  
56 Richardson, 1992; Inglett et al., 2012), salinity (Bartlett et al., 1987; Weston et al., 2011) and  
57 vegetation biomass and type (Inglett et al., 2012; Kandel et al., 2013) may have strong controlling  
58 effects on greenhouse gas emissions from wetlands. Decomposition of organic matter in wetland  
59 soil is strongly dependent on temperature, and therefore, both CO<sub>2</sub> and CH<sub>4</sub> emissions from  
60 decomposition processes tend to increase with increasing soil temperature (Herbst et al., 2011;  
61 Inglett et al., 2012). The optimum temperature for methanogenesis is around 20-30 °C, depending  
62 on the community of methanogenic archaea (Svensson, 1984). However, methanogens are strictly  
63 anaerobic, and for methanogenesis to take place the redox potential must be as low as -200 mV,

64 and other competing terminal electron acceptors must have been reduced ( $O_2$ ,  $NO_3$  and  $SO_4$ )  
65 (Mitsch and Gosselink, 2007). The position of the water table is therefore an important controlling  
66 factor on  $CH_4$  emissions, as high water tables lead to oxygen depletion and thus low redox  
67 potentials, which favors methanogenesis in the wetland soil (Grunfeld and Brix, 1999).  
68 Couwenberg et al. (2011) found that  $CH_4$  emissions in peatlands were practically zero when the  
69 water table was below -20 cm, whereas the emissions varied between near zero and 500 kg  $CH_4$   
70  $ha^{-1} y^{-1}$  when the water table was above -20 cm. The more oxidized conditions associated with low  
71 water tables favor  $CH_4$  oxidation by aerobic methanotrophic bacteria (Whalen, 2005), as well as  
72 aerobic decomposition of organic matter, both processes emitting  $CO_2$ . It can therefore be difficult  
73 to predict gas emissions under field conditions, as both soil temperatures and water tables may be  
74 subject to large seasonal variations.

75 The presence of vegetation affects  $CO_2$  fluxes primarily by photosynthesizing and by increasing the  
76 total ecosystem respiration (Han et al., 2013; Kandel et al., 2013). However, the vegetation may  
77 also affect  $CH_4$  emissions. Oxygen released from roots create aerobic microsites in the rhizosphere  
78 (Brix, 1994), which favors  $CH_4$  oxidation by aerobic methanotrophs (Grunfeld and Brix, 1999). On  
79 the other hand, a high primary production also increases the available carbon substrate for  
80 methanogens via biomass decomposition and root exudation and can thus lead to higher  $CH_4$   
81 emissions (Van der Nat and Middelburg, 2000; Whiting and Chanton, 1993). In addition, wetland  
82 plants with internal air spaces (aerenchyma) provide an additional gas transport pathway, apart  
83 from diffusion and ebullition from the sediment, that can enhance  $CH_4$  emissions (Brix et al.,  
84 1996; Henneberg et al., 2012; Sorrell and Boon, 1994). Methane produced in the soil can be  
85 transported through the aerenchyma of the plant tissue and bypass the water column, where it  
86 otherwise could have been oxidized by methanotrophs before reaching the atmosphere (Whalen,  
87 2005). Thus, wetland vegetation can both decrease and enhance  $CH_4$  emissions depending on the  
88 specific site conditions and type of vegetation.

89 Acute saltwater intrusion to freshwater wetlands has been reported to increase soil respiration  
90 and lead to elevated  $CO_2$  emissions (Chambers et al., 2011; Weston et al., 2011). However, coastal  
91 wetlands with high salinity usually emit less  $CH_4$  than less saline wetlands (Bartlett et al., 1987;  
92 Poffenbarger et al., 2011). This has been explained by the high concentration of sulphate ions

93 (SO<sub>4</sub><sup>2-</sup>) in sea water, and the consequent high activity of sulphate reducing bacteria which  
94 outcompete methanogens for organic substrate (Bartlett et al., 1987). Poffenbarger et al. (2011)  
95 analyzed CH<sub>4</sub> and salinity data from a number of coastal wetlands and found a threshold salinity  
96 level of 18 ppt, above which the wetlands emitted significantly less CH<sub>4</sub> than those with a lower  
97 salinity.

98 Although many factors are known to influence CO<sub>2</sub> and CH<sub>4</sub> emissions from coastal wetlands, it is  
99 still unclear which factors are most important under field conditions when they are all acting  
100 simultaneously. Knowledge of the interactive effects of the factors driving greenhouse gas  
101 emissions is a prerequisite to being able to manage wetlands in a way that minimizes greenhouse  
102 gas emissions, and to predict the effects of future climate change on greenhouse gas emissions  
103 from wetlands. The objectives of this study were (i) to quantify the CH<sub>4</sub> emission and ecosystem  
104 respiration in the dominant wetland communities in a coastal wetland ecosystem, (ii) to assess the  
105 seasonal variation in CH<sub>4</sub> emission and ecosystem respiration in different plant communities, and  
106 (iii) to determine the main controlling factors for CH<sub>4</sub> emission and ecosystem respiration under  
107 field conditions.

## 108 **2 Materials and Methods**

### 109 **2.1 Study sites**

110 The Liaohe Delta is situated in the Liaoning Province in northeast China and comprises a wetland  
111 area of around 1,280 km<sup>2</sup> (Li et al. 2012). About 786 km<sup>2</sup> of that is marsh vegetated by common  
112 reed (*Phragmites australis* (Cav.) Trin. Ex Steud). The reed marshes in the Liaohe Delta represent  
113 probably the largest reed fields in the world (Brix et al., 2014). The growing conditions for common  
114 reed in the delta marshes have been improved since the 1960s by a freshwater irrigation  
115 management practice, that has washed away much of the soil salinity, and as a result, led to an  
116 expansion of the reed fields and an increase in productivity (Ji et al., 2009). The reed biomass is  
117 extensively used for paper production (Ma et al., 1993), and the hydrology is therefore regulated  
118 to maximize the biomass yield (Brix et al., 2014). Apart from reed marshes, the main wetland types  
119 in the Liaohe Delta are tidal saltmarshes vegetated by *Suaeda salsa* (L.) Pall., III (seablite), and rice  
120 paddies planted with *Oryza sativa* L. (Asian rice). The wetlands of the Liaohe Delta are important

121 breeding areas for many endangered bird species, and are designated as a Shuangtaizihekou  
122 (Liaohekou) National Nature Reserve since 1986 and also listed as a Ramsar site since 2004 (Li et  
123 al., 2012). However, the wetlands are adversely affected by the polluted water from the Liaohe  
124 River (Zhang et al., 2010) and oil extraction activities, as the Liaohe Delta contains the third largest  
125 oil field in China (Zhu et al., 2010).

126 Five study sites were selected to embrace the main wetland types of the delta. The five study sites  
127 included two *Suaeda* marshes, one created and one natural ('Suaeda1' at 40°52'11.09"N;  
128 121°36'21.72"E and 'Suaeda2' at 40°57'38.62"N; 121°48'20.03"E, respectively), two *Phragmites*  
129 wetlands for paper production, ('Phrag1' at 40°52'22.34"N; 121°36'08.89"E and 'Phrag2' at  
130 41°09'33.75"N; 121°47'42.71"E) and a rice paddy ('Rice' at 41°10'38.69"N; 121°41'17.28"E).

## 131 **2.2 Gas sampling and analysis**

132 Gas samples for estimation of CO<sub>2</sub> and CH<sub>4</sub> emission were collected monthly from April to  
133 November 2012, using the static chamber method (Livingston and Hutchinson, 1995). Six  
134 quadratic metal frames (0.6 x 0.6 m) were permanently installed in each study site, and wooden  
135 boardwalks were built to facilitate access to the frames without disturbing the soil. Small holes  
136 were drilled in the sides of the frames just at the ground surface to facilitate water exchange  
137 between the inside of the frames and the surrounding wetland between sampling events. These  
138 holes were plugged during sampling. At each sampling event, a white plastic chamber (0.55 x 0.55  
139 x 0.30 m) was placed over the metal frame and an airtight seal was created by water (about 1 cm  
140 deep) within a trough inside the frame. The chambers were modified from past designs deployed  
141 in shaded forested wetlands (Krauss and Whitbeck, 2012; Yu et al., 2008) by using aluminum foil to  
142 cover all inside walls to block out light and prevent photosynthesis completely and to minimize  
143 temperature changes. Transparent and opaque chambers have been shown to provide similar CH<sub>4</sub>  
144 flux estimates (Minke et al., 2014). If the vegetation was taller than the chamber, the plants were  
145 bent to fit inside the chamber. At Phrag2, however, the plants grew so tall that they had to be cut  
146 in June; we limited what we had to cut as much as possible. A small fan was used to mix the air  
147 inside the chamber during sampling, and a PVC tube with the outer end placed in water was used  
148 to equilibrate the air pressure inside the chamber with the outside air pressure. Gas samples were  
149 taken from the chamber through a rubber septum using a 15 mL plastic syringe, and immediately

150 transferred into pre-evacuated 10 mL glass vials with a thick rubber cap and an aluminum lid. The  
151 first sample was taken immediately after placing the chamber onto the frame, and four additional  
152 samples were taken with 20 minute intervals. The temperatures at a soil depth of 10 cm and the  
153 air temperature in the chamber were recorded at each sampling time. The gas samples were  
154 stored at room temperature for a maximum of one week before analysis. For comparison, the CO<sub>2</sub>  
155 flux in each chamber was also measured in situ during separate 1 minute incubations on the same  
156 day using a portable infrared gas analyzer (LI-COR 8100, Lincoln, NE, USA).

157 The concentrations of CO<sub>2</sub> and CH<sub>4</sub> in the gas samples were analyzed in 0.6 mL injections on a  
158 TRACE Ultra GC-TCD (Thermo Fischer Scientific Inc., Waltham, MA, USA) at Qingdao Institute of  
159 Marine Geology and an Agilent 7890A at the Ocean University of China, respectively. Signals from  
160 the GCs were recorded in GC/MSD ChemStation Software (Agilent Technologies, Inc., Santa Clara,  
161 CA, USA) and the peak areas used to calculate the concentrations of CH<sub>4</sub> and CO<sub>2</sub>. Gas emissions in  
162 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup> and mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup> (using the weight of the whole molecules of CH<sub>4</sub> and CO<sub>2</sub>,  
163 respectively) were determined from the increase in concentration in the chambers over time using  
164 linear regression analysis. Regression lines with a coefficient of determination (R<sup>2</sup>) < 0.6 were not  
165 included, except in cases where it was obvious that the low R<sup>2</sup> value was due to extremely low gas  
166 fluxes (zero or near-zero fluxes). In a few cases, extremely deviant data were excluded. Because of  
167 technical problems, no data on CO<sub>2</sub> emissions are available from Phrag1 in April and from Suaeda1  
168 and Suaeda2 in May, and no data on CO<sub>2</sub> and CH<sub>4</sub> emissions in August from Phrag1.

169 Cumulative CO<sub>2</sub> and CH<sub>4</sub> emissions at each site were calculated as the integral of the mean gas  
170 emissions (in mg m<sup>-2</sup> d<sup>-1</sup>) from the monthly sampling campaigns. As the gas sampling chambers  
171 were darkened, CO<sub>2</sub> emissions were assumed to be constant on a daily and nightly basis. And  
172 although some studies have found diurnal variations in CH<sub>4</sub> emissions (Käki et al., 2001; Neubauer  
173 et al., 2000; Tong et al., 2013), no consistent pattern has been found. Hence, we assumed that the  
174 CH<sub>4</sub> emissions were also constant on a daily basis.

### 175 **2.3 Environmental parameters**

176 The water table was measured in a piezometer at each study site, and the soil surface level  
177 differences among the six plots at each site were used to calculate individual water tables for each

178 plot. Water samples for salinity and pH analyses were taken from the piezometer, and measured  
179 using a Jenco 6010 microcomputer based pH/mV/temperature portable meter (Jenco Electronics,  
180 Ltd., Shanghai, China).

181 The aboveground biomass inside the plots was estimated using a non-destructive method. In the  
182 *Phragmites* wetlands, the heights of all shoots inside the frames were measured, and 25 shoots  
183 encompassing the range of heights in the frames were harvested outside the frames. In the  
184 *Suaeda* wetlands, the plant density inside the frames was counted and 20x20 cm plots outside the  
185 frame with a similar plant density were harvested. The plants were dried at 60°C and weighed,  
186 and the biomass inside the plots was calculated from a regression analysis between plant height  
187 and dry mass (*Phragmites*) and between plant density and dry mass (*Suaeda*). In the rice paddy,  
188 five rice plants outside the frames were harvested, dried and weighed, and the biomass within the  
189 frames was estimated based on the number of plants.

190 Soil core samples were taken to 5 cm depth from the topsoil near each frame using a 5 cm  
191 diameter steel cylinder. The samples were dried to constant weight at 60°C for determination of  
192 bulk density and water content. Soil redox potentials (Eh) were measured using platinum  
193 electrodes installed at a depth of 10 cm at least 24 hours before measuring. Redox electrodes  
194 were referenced against a calomel electrode.

195 Two soil core samples were collected to 4 cm depth at each site the following year, mixed and  
196 analyzed for selected mineral elements and available nutrients. Total N and TC were analyzed on  
197 oven-dried subsamples ground to pass a 2 mm sieve, on a Perkin Elmer 2400 Series II CHNS/O  
198 elemental analyzer (Perkin Elmer, Inc., Waltham, MA, USA). For determination of Org-C, another  
199 set of subsamples was treated with 4M HCl (Craft, 2007) to remove inorganic carbon before  
200 analysis on the same instrument. Available nutrients were extracted by the Mehlich-III method  
201 (Mehlich, 1984), using an extraction solution prepared from 22.98 mL concentrated CH<sub>3</sub>COOH,  
202 40.0 g NH<sub>4</sub>NO<sub>3</sub>, 1.12 g NH<sub>4</sub>F, 1.68 mL concentrated HNO<sub>3</sub>, 0.58 g EDTA and 1,600 mL deionized  
203 water, diluted to 2 L. Air-dried soil subsamples were ground to pass a 1 mm mesh. 2.5 g of the  
204 ground soil were shaken with 25 mL extraction solution on a reciprocating oscillator for 5 minutes  
205 and then centrifuged for 20 minutes. The supernatant was diluted ten times and analyzed for Ca,  
206 Cu, Fe, K, Mg, Mn, P and Zn by ICP-OES (Optima 2000 DV, Perkin Elmer, USA).



## 207 2.4 Statistical analysis

208 The in situ measurements of CO<sub>2</sub> emissions with the IRGA were used in the statistical analyses.  
209 Methane emissions and ecosystem respiration (R<sub>eco</sub>) were analyzed by Site and Time with Plot as a  
210 random factor nested within Site, in a repeated-measures setup using the General Linear Model  
211 (GLM) procedure of Statgraphics Centurion XVI (Statpoint Technologies, Inc., Warrenton, Virginia,  
212 USA). The Bonferroni post-hoc test was used to identify significant differences between different  
213 sites at the 5 % significance level. Data of CH<sub>4</sub> emissions and R<sub>eco</sub> were log-transformed to meet  
214 the assumption of equal variances, which was checked using Levene's test (p>0.05). Since the  
215 dataset included a few negative gas flux values, a constant was added to the fluxes (CH<sub>4</sub> flux+0.6  
216 and R<sub>eco</sub>+25, respectively) before applying the log-transformations. Data from April, May and  
217 August were excluded from the analyses due to missing data at some sites.

218 Linear mixed effects models (multiple regressions) using R version 3.0.1 (Team, 2013) were used to  
219 assess the relations between the measured environmental factors and CO<sub>2</sub> and CH<sub>4</sub> emissions,  
220 respectively. The response variables were CO<sub>2</sub> and CH<sub>4</sub> emissions. The fixed effects were plant  
221 species (categorical variable), soil temperature (SoilT), water table (WT), aboveground biomass  
222 (Biomass) and Salinity (continuous variables). The random effects were Site and Plot. An  
223 interaction effect between plant species and aboveground biomass was also included. The effect  
224 of each variable or interaction was evaluated by removing the variable/interaction from the  
225 original model and using a likelihood ratio chi-square test to test for significant differences at the  
226 5% significance level between the original model and the model excluding the variable/interaction.  
227 Data of CO<sub>2</sub> and CH<sub>4</sub> emissions were log-transformed as described before to meet the assumptions  
228 of normality and equal variances. The original mixed effects model for CO<sub>2</sub> and CH<sub>4</sub> emissions,  
229 respectively, was in the form:

$$230 \text{Log}_{10}(\text{gas flux})_i = \beta_{1i} \cdot \text{Biomass}_i + \beta_2 \cdot \text{SoilT} + \beta_3 \cdot \text{Salinity} + \beta_4 \cdot \text{WT} + b_1(\text{Site}) + b_2(\text{Plot}) + \varepsilon_i \quad (1)$$

231 where  $\beta_1$  is a coefficient specific for plant species  $i$ ,  $\beta_2$ ,  $\beta_3$  and  $\beta_4$  are coefficients for fixed effects  
232 common for all plant species,  $b_1$  and  $b_2$  are coefficients for the random effects and  $\varepsilon_i$  is the  
233 residual error for plant species  $i$ .

## 234 **3 Results**

### 235 **3.1 Environmental parameters**

236 The water tables varied greatly over the season, particularly at Phrag2 where the water table  
237 ranged from -35 to +27 cm, and at Suaeda1 where it ranged from -43 to +15 cm (Fig. 1c). At the  
238 two *Phragmites* wetlands, the water tables were managed to maximize the yield of *Phragmites*  
239 biomass. Hence, the water tables at these sites were above the soil surface during most of the  
240 growing season. The water tables at the two *Suaeda* wetlands fluctuated greatly due to tidal  
241 variations, but the water tables were at the time of sampling usually below the soil surface. At the  
242 rice paddy, the water table was fairly stable around +10 cm from June to September due to  
243 regulation according to agricultural practice.

244 Soil temperatures at all sites increased from 18-22°C in May to 23-28°C in August, and then  
245 declined to 0-7°C in November (Fig. 1d). We do not have temperature data from the months prior  
246 to our sampling, but usually the soils in the delta are frozen until April, whereafter the  
247 temperature increases over a few weeks.

248 The amount of aboveground biomass was basically zero during the first sampling campaign in late  
249 April. Thereafter, both *Suaeda* and *Phragmites* grew rapidly reaching aboveground biomasses in  
250 June of ~800 g dry mass m<sup>-2</sup> for *Suaeda* and ~400 g dry mass m<sup>-2</sup> for *Phragmites* before the cutting  
251 in June (Fig. 1e). In the rice paddy, the rice plants were planted in late June. Hence the  
252 development of biomass in the rice paddies occurred much later than in the natural *Suaeda* and  
253 *Phragmites* wetlands.

254 The salinity at Suaeda1 was 32-39 ppt during most of the sampling period (Fig. 1f). At Suaeda2 the  
255 salinity was lower: 10-15 ppt from May to July and then decreasing to 5-6 ppt in August to  
256 December. In the *Phragmites* wetlands, the salinities varied between 2 and 19 ppt depending on  
257 the water management scheme. The highest salinities were found at Phrag1. At the rice paddy the  
258 salinity was constantly low at around 2 ppt.

259 Soil bulk density varied between 0.93 g cm<sup>-3</sup> at Phrag2 to 1.50 g cm<sup>-3</sup> at Suaeda1, and soil water  
260 content between 27% at Suaeda1 and 48% at Phrag2 (Table 1). The mean redox potential was  
261 highest at Suaeda1 (+101 mV) and lowest at Phrag1 (-127 mV). The mean soil water pH was in the  
262 interval 7.12 – 7.70 at all sites

263 All topsoils consisted largely of fine silt and clay and had a low content of organic matter (Org-C <  
264 2% of the dry matter). However, the contents of organic carbon (12%) and nitrogen (1%) were  
265 markedly higher at Phrag2 than at the other sites (Table 1). At Phrag1, the contents of organic  
266 carbon (1.8%) and nitrogen (0.17%) were 2-3 times higher than at the Suaeda sites and the rice  
267 paddy. Differences in other analyzed mineral elements were less pronounced and probably  
268 reflected the predominantly mineral composition of the soils, except for the concentration of P  
269 which was higher at Phrag2 and the rice paddy than at the other sites.

### 270 3.2 CH<sub>4</sub> emissions

271 There were large variations in CH<sub>4</sub> emission rates both among sites and over the season (Fig. 1a)  
272 and these differences were statistically significant (Table 2). The highest CH<sub>4</sub> emission rates were  
273 found at Phrag2 and at the rice paddy. Peak emissions were 2.5 mg m<sup>-2</sup> h<sup>-1</sup> at both sites although  
274 the peak values were measured in July at Phrag2 and in August at the rice paddy (Fig. 1a). The  
275 highest CH<sub>4</sub> emission rates at Phrag1 (around 0.7 mg m<sup>-2</sup> h<sup>-1</sup>) were only a fourth of those at  
276 Phrag2. At the two *Phragmites* wetlands, the CH<sub>4</sub> emission rates were close to zero in April-May,  
277 increased rapidly from June to July, and declined again after August. At the rice paddy, the CH<sub>4</sub>  
278 emission rates were near zero in June, low in July (0.25 mg m<sup>-2</sup> h<sup>-1</sup>), increased very sharply from  
279 July to August and thereafter declined. At the *Suaeda* wetlands, the CH<sub>4</sub> emission rates were close  
280 to zero throughout the sampling period. Means and ranges of CH<sub>4</sub> emission rates over the whole  
281 sampling period, and significant differences (p<0.05) among sites, are shown in Table 4.

282 The CH<sub>4</sub> emission rates at sites with significant emissions (Phrag1, Phrag2 and Rice) were positively  
283 related to both soil temperature and water table (Table 3; Fig. 3). The CH<sub>4</sub> emission rates were less  
284 than 1 mg m<sup>-2</sup> h<sup>-1</sup> at temperatures below 18°C and at water tables below the soil surface. The  
285 highest CH<sub>4</sub> emission rates were measured at Phrag2 when both the temperature and the water  
286 table were high (Fig. 3). The CH<sub>4</sub> emissions decreased significantly (Table 3) with increasing  
287 salinity, as CH<sub>4</sub> emission rates were less than 1 mg m<sup>-2</sup> h<sup>-1</sup> at salinity levels above 18 ppt (Fig. 4). At  
288 the highest salinity levels at Suaeda1 (32-38 ppt), CH<sub>4</sub> emission rates were practically zero.

289 Cumulative CH<sub>4</sub> emissions over the entire growing season in 2012 were highest at Phrag2 with 6.1  
290 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup>, corresponding to 154 g CO<sub>2</sub>-equivalents m<sup>-2</sup> y<sup>-1</sup> (Fig. 2, Table 4). These emissions  
291 were about 1.5 times higher than the cumulative CH<sub>4</sub> emissions from the rice paddy, and about

292 five times higher than the CH<sub>4</sub> emissions from Phrag1. CH<sub>4</sub> emissions from the *Suaeda* wetlands  
293 were negligible.

### 294 **3.3 Ecosystem respiration (R<sub>eco</sub>)**

295 The measured flux of CO<sub>2</sub> in the darkened chamber is the sum of the flux of CO<sub>2</sub> from the soil and  
296 the respiration of the plant tissue inside the chambers. We here refer to this as the ecosystem  
297 respiration (R<sub>eco</sub>). The ecosystem respiration rates varied significantly both among sites and over  
298 time (Fig. 1b, Table 2). The highest ecosystem respiration rates at the rice paddy and at Phrag2  
299 (2,400 and 2,300 mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>, respectively) were twice as high as the highest R<sub>eco</sub> at Phrag1 and  
300 three times higher than the R<sub>eco</sub> at the two *Suaeda* wetlands. At Phrag2, R<sub>eco</sub> was highest in June  
301 and July, whereas at the rice paddy, the R<sub>eco</sub> was low at this time of the year and highest in August  
302 (Fig. 1b). It should, however, be mentioned that the *Phragmites* stems at Phrag2 were cut in June.  
303 Hence, the biomass within the chambers from July and onwards was lower than the biomass in  
304 the surrounding reed vegetation. Overall, the ecosystem respiration rates were significantly  
305 related to plant biomass, soil temperature and salinity (Table 3) whereas water table had no  
306 significant effect on R<sub>eco</sub> (p>0.05).

307 The cumulative CO<sub>2</sub> emissions, without accounting for photosynthetic CO<sub>2</sub> uptake, varied between  
308 1.7 kg m<sup>-2</sup> y<sup>-1</sup> in the *Suaeda* wetlands to 3.0-4.4 kg m<sup>-2</sup> y<sup>-1</sup> in the *Phragmites* (Table 4). The  
309 cumulative CO<sub>2</sub> emission in the rice paddy was in-between this range (3.3 kg m<sup>-2</sup> y<sup>-1</sup>).

310

## 311 **4 Discussion**

### 312 **4.1 CH<sub>4</sub> emissions**

313 Over one growing season in 2012, the two *Phragmites* wetlands emitted on average 0.15 and 1.01  
314 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup> (Phrag1 and Phrag2, respectively) and the rice paddy 0.75 mg m<sup>-2</sup> h<sup>-1</sup>, whereas the  
315 emissions from the two *Suaeda* wetlands were negligible. The large differences in CH<sub>4</sub> emission  
316 rates among the five sites can be explained by the differences in soil organic matter, salinity and  
317 water tables, and, to some extent, vegetation type. For methanogenesis to take place there must  
318 be a sufficient amount of labile organic substrate available (Mah et al., 1977), such as dead plant  
319 material from the previous growing season and root exudates from the standing vegetation (Mann  
320 and Wetzel, 1996; Zhai et al., 2013). Previous studies have reported increasing CH<sub>4</sub> emission rates

321 with increasing content of soil organic matter in different types of wetlands (Le Mer and Roger,  
322 2001; Picek et al., 2007; Serrano-Silva et al., 2014; Sha et al., 2011; Tanner et al., 1997). At Phrag2,  
323 where CH<sub>4</sub> emission rates were significantly higher than at the other sites, there was a many-fold  
324 higher content of organic carbon and nitrogen in the soil compared to the soils at the other sites,  
325 and the reeds at Phrag2 had a very dense root system in the upper soil layers. Thus, the reason for  
326 the high CH<sub>4</sub> emission rates at Phrag2 was most likely the higher content of organic substrate for  
327 methanogenesis, originating from dead plant residues and from root exudates. At the rice paddy,  
328 where the second highest CH<sub>4</sub> emissions were measured, the organic content of the soil was low,  
329 but the soil C:N ratio was lower (8.4) than the ratios at the other sites probably resulting from  
330 different plant inputs into the soil. A lower C:N ratio of the organic matter in the soil may increase  
331 organic matter lability by decreasing nitrogen limitation for decomposers (Hodgkins et al., 2014).  
332 However, the fact that the rice paddy was constantly flooded throughout the growing season  
333 probably also stimulated methanogenesis and CH<sub>4</sub> emission.

334 Both *P. australis* and rice have well developed aerenchyma in roots, rhizomes and stems, which  
335 provides them with a high ability to transport gases between the soil and the atmosphere through  
336 the plant tissue (Brix et al., 1996; Singh and Singh, 1995). When CH<sub>4</sub> is transported from the soil  
337 through the air-space tissues of the plants, it bypasses the aerobic zone in the upper part of the  
338 soil and the water column, where CH<sub>4</sub> otherwise could have been oxidized by methanotrophic  
339 bacteria (Whalen, 2005). Plant-mediated transport has been reported to be the main pathway of  
340 CH<sub>4</sub> transport from the soil to the atmosphere and constituting as much as 60-90 % of the CH<sub>4</sub>  
341 emissions (Butterbach-Bahl et al., 1997; Huang et al., 2005). In the present study, transport of CH<sub>4</sub>  
342 through the air-space tissue of the plants may explain the relatively high CH<sub>4</sub> emission rates from  
343 the *Phragmites* wetlands and the rice paddy, while the lack of well-developed aerenchyma in *S.*  
344 *salsa* is consistent with the negligible emission rates from the *Suaeda* wetlands. The aboveground  
345 biomass *per se* probably had no effect on the plant-mediated CH<sub>4</sub> emissions, as CH<sub>4</sub> has been  
346 shown to be mainly emitted through micropores in the basal parts of rice plants (Nouchi et al.,  
347 1990) and through the basal internodes of *P. australis* (Brix, 1989). Also, Henneberg et al. (2012)  
348 showed in a manipulation experiment with *Juncus effusus* that aboveground biomass was  
349 unimportant for the CH<sub>4</sub> transport through the plants, whereas the removal of fine roots and root  
350 tips of coarse roots led to significant reductions in plant-mediated CH<sub>4</sub> transport. Thus, it is likely

351 that the extensive root system of the reeds at Phrag2 contributed to the high CH<sub>4</sub> emission rates  
352 at this site.

353 At salinity levels above 18 ppt the CH<sub>4</sub> emission rates were always lower than 1 mg m<sup>-2</sup> h<sup>-1</sup> across  
354 all sites (Fig. 4). This is consistent with Poffenbarger et al. (2011) who found a salinity threshold of  
355 18 ppt, above which CH<sub>4</sub> emission rates were significantly lower than at lower salinity levels. The  
356 effect of salinity has been explained by the high concentrations of SO<sub>4</sub><sup>2-</sup> in seawater, which inhibit  
357 CH<sub>4</sub> production due to competition from sulphate reducing bacteria (Bartlett et al., 1987; D'Angelo  
358 and Reddy, 1999). Thus, the lack of CH<sub>4</sub> emissions at the *Suaeda* sites is most likely an effect of the  
359 high salinity, particularly at the Suaeda1 site where salinities were up to 35 ppt. The salinity was,  
360 however, significantly lower at the Suaeda2 site with salinities of 5-15 ppt, and yet there were no  
361 CH<sub>4</sub> emissions as SO<sub>4</sub><sup>2-</sup> concentrations were still high enough to inhibit methanogenesis. At Phrag2,  
362 on the other hand, CH<sub>4</sub> emission rates were high although the water salinity was occasionally as  
363 high as 15 ppt. These seemingly contradictory results can be explained by the fact that a high  
364 salinity in the water mainly affects the upper soil layers, but not necessarily the deeper layers.  
365 Therefore, methanogens may be outcompeted by sulphate reducing bacteria in the upper layers  
366 of the soil, but CH<sub>4</sub> can still be produced in the deeper soil layers where all SO<sub>4</sub><sup>2-</sup> have been  
367 reduced. The roots of *P. australis* grow to a soil depth of at least 40-60 cm, and CH<sub>4</sub> can therefore  
368 be transported from the deeper anoxic zone through the air-space tissue of the plants to the  
369 atmosphere. Thus, the relatively high salinity at Phrag2 probably inhibited methanogenesis in the  
370 upper soil layers, but the CH<sub>4</sub> produced in the deeper soil layers were still transported to the  
371 atmosphere through the plants. At the *Suaeda* wetlands, the generally low and fluctuating water  
372 tables indicate that the anaerobic zone where methanogenesis can take place was at a deeper soil  
373 depth than at the *Phragmites* wetlands. The roots of *S. salsa* lack aerenchyma and are generally  
374 restricted to the upper 20 cm of the soil, and are therefore ineffective conduits for CH<sub>4</sub> from the  
375 deeper soil layers to the atmosphere. Thus, although salinity levels at Suaeda2 were not always  
376 high, any CH<sub>4</sub> that may have been produced in the soil did not reach the atmosphere because of  
377 CH<sub>4</sub> oxidation in the upper soil layer. At the rice paddy, the low salinity of around 2 ppt seemingly  
378 had no inhibitory effect on the CH<sub>4</sub> production and emission.

379 The water table is an important parameter affecting the CH<sub>4</sub> emission rate. The highest CH<sub>4</sub>  
380 emissions occurred at the three sites where the water exchange and water table were managed to  
381 maximize the reed biomass (Phrag1, Phrag2) and crop yield (Rice) whereas very low CH<sub>4</sub> emission  
382 rates were found at the two *Suaeda* wetlands with a natural tidal hydrology. At the rice paddy, the  
383 soil was continuously flooded from June until September, and the two *Phragmites* wetlands were  
384 more or less flooded from June until October, resulting in low redox potentials and relatively high  
385 CH<sub>4</sub> emission rates. The soils at the tidally influenced *Suaeda* wetlands were periodically drained  
386 and hence partly oxidized inhibiting CH<sub>4</sub> production. When water tables at the *Phragmites*  
387 wetlands and the rice paddy were below the soil surface, the CH<sub>4</sub> emission rates were always <1  
388 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup> probably because CH<sub>4</sub> produced in deeper soil layers was oxidized in the upper oxic  
389 soil layers, reducing the amount of CH<sub>4</sub> reaching the atmosphere. When the water tables  
390 approached the soil surface, the CH<sub>4</sub> emission rates increased. This is in agreement with the  
391 findings of Zhu et al. (2014), who reported that the seasonal CH<sub>4</sub> emissions from an herbaceous  
392 peatland were highly linked to water table fluctuations, and that the water table was the main  
393 environmental driver for CH<sub>4</sub> emissions over a single growing season, whereas soil temperature  
394 was important on a longer time scale. The important effect of water table on CH<sub>4</sub> emission rates is  
395 in agreement with observations in other studies (e.g. Bridgham et al., 2006; Couwenberg et al.,  
396 2011; Le Mer and Roger, 2001; Serrano-Silva et al., 2014). However, in the present study both soil  
397 water table and temperature were important drivers.

398 The large seasonal variations in CH<sub>4</sub> emission rates at Phrag1, Phrag2 and Rice were primarily  
399 related to the variations in soil temperatures. The highest CH<sub>4</sub> emission rates occurred during the  
400 summer months July-September, when temperatures were relatively high. We found an  
401 exponential relationship between soil temperature and CH<sub>4</sub> emission rates (Fig. 3) similar to those  
402 reported elsewhere (Herbst et al., 2011; Inglett et al., 2012) in accordance with the temperature  
403 dependency of the methanogenic bacteria. Furthermore, the amount of labile organic carbon  
404 substrates from root exudates can be stimulated by high temperatures as Zhai et al. (2013) found  
405 significantly higher root exudation rates from *P. australis* roots at 20°C than at 10°C. Also the  
406 plant-mediated CH<sub>4</sub> transport may be accelerated at higher temperatures as Hosono & Nouchi  
407 (1997) reported that the CH<sub>4</sub> transport through rice plants was twice as high at a rhizosphere  
408 temperature of 30°C as compared to the transport at 15°C. Thus, the high CH<sub>4</sub> emission rates at

409 both Phrag2 and Rice during the warmest months of the year were probably due to the high  
410 temperature and its stimulating effect on the activity of the methanogenic bacteria, the root  
411 exudation rates and the effectivity of the plant-mediated transport. At soil temperatures below  
412 18°C, which occurred before June and after September, CH<sub>4</sub> emission rates were consistently low  
413 (<1 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup>). In the spring, the low rates might be associated with a time-lag in the growth  
414 of methanogens as the temperature was increasing over a relatively short period. In the autumn  
415 the low rates might be influenced by low availability of organic carbon, as most carbon might have  
416 been 'burned off' during the hot summer months.

#### 417 **4.2 Ecosystem respiration (R<sub>eeco</sub>)**

418 Ecosystem respiration rates were highest in June-July at the *Phragmites* wetlands, June-August at  
419 the *Suaeda* wetlands and August at the rice paddy. The differences among the sites can be  
420 explained by the differences in soil organic matter and biomass, whereas the variations over time  
421 can be explained mainly by soil temperature and to some extent by differences in biomass. The  
422 seasonal pattern of ecosystem respiration was closely related to that of soil temperature at all  
423 sites, which suggests that temperature was the main controlling factor for ecosystem respiration.  
424 This is in agreement with the findings of other studies (Bridgham and Richardson, 1992; Han et al.,  
425 2013; Happell and Chanton, 1993; Kandel et al., 2013; Krauss et al., 2012; Pulliam, 1993).  
426 However, biomass respiration also contributed to the ecosystem respiration rates, particularly late  
427 in the season when the aboveground biomass was highest. At Phrag1, Suaeda1 and Suaeda2, the  
428 seasonal pattern of ecosystem respiration rates correlated to that of the aboveground biomass,  
429 indicating that plant respiration may have constituted a large part of the total ecosystem  
430 respiration at these sites. This is in agreement with Kandel et al. (2013), who found that plant  
431 respiration contributed with about 50% of the total ecosystem respiration in a cultivated peatland  
432 during the summer months, and Xu et al. (2014), who found ten times higher CO<sub>2</sub> emissions from  
433 marshes with plant communities than from those without. Also, the difference in ecosystem  
434 respiration rates between the two *Suaeda* wetlands corresponded to the differences in *Suaeda*  
435 biomass. However, at Phrag2 nearly all CO<sub>2</sub> emissions came from the soil and the belowground  
436 biomass, since only short stems were left behind after cutting the reeds in June. At the rice paddy,  
437 the ecosystem respiration peaked in August when the aboveground biomass was only about 100 g  
438 m<sup>-2</sup>. The aboveground rice biomass continued to increase after August, but the ecosystem



439 respiration decreased drastically, indicating that soil respiration constituted the main part of  
440 ecosystem respiration at the rice paddy.

#### 441 **4.3 Cumulative emissions**

442 The two *Suaeda* wetlands were net CH<sub>4</sub> sinks whereas the two *Phragmites* wetlands and the rice  
443 paddy were net CH<sub>4</sub> sources during April to November 2012. Although the peak CH<sub>4</sub> emission rates  
444 at the rice paddy were similar to those at Phrag2, the cumulative CH<sub>4</sub> emission rates from Phrag2  
445 were 1.5 times higher than those from Rice. The cumulative CO<sub>2</sub> emitted from ecosystem  
446 respiration followed a similar pattern, with Phrag2 emitting 1.3 times more CO<sub>2</sub> than the rice  
447 paddy. Thus, on a yearly basis Phrag2 emitted the highest amounts of both CH<sub>4</sub> and CO<sub>2</sub> per unit  
448 area, and also the most CH<sub>4</sub> relative to CO<sub>2</sub>. Since CO<sub>2</sub> emissions from vegetated ecosystems are  
449 counteracted by photosynthetic CO<sub>2</sub> uptake and possibly carbon sequestration, the CO<sub>2</sub> emissions  
450 measured as ecosystem respiration does not contribute to the greenhouse effect. However, the  
451 CH<sub>4</sub> emissions from wetland ecosystems contribute to the radiative forcing, and therefore CH<sub>4</sub>  
452 emission rates should be minimized. It is, however, the balance between carbon sequestrations on  
453 the one hand and CH<sub>4</sub> emission on the other hand that determines if a particular wetland can be  
454 considered to be a net source or a net sink for radiative greenhouse gases (Mitsch et al., 2013).  
455 Based on the present study, it is unfortunately not possible to estimate the carbon sequestration  
456 of the different wetland communities.

#### 457 **4.4 CH<sub>4</sub> emission rates and R<sub>ecco</sub> compared to other studies**

458 The CH<sub>4</sub> emission rates and seasonal pattern at Phrag2 were similar to those measured by Huang  
459 et al. (2005) from a reed wetland in the Liaohe delta, where CH<sub>4</sub> emission rates varied from -0.97  
460 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup> in early May to 2.73 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup> in early September. The average CH<sub>4</sub> emission  
461 rate at Phrag2 was within the range of CH<sub>4</sub> emission rates from reed wetlands in other parts of  
462 China, varying from 0.75 mg m<sup>-2</sup> h<sup>-1</sup> (Xu et al., 2014) to 5.13 mg m<sup>-2</sup> h<sup>-1</sup> (Tong et al., 2010). The  
463 *Suaeda* wetlands had CH<sub>4</sub> emission rates very similar to those from a *Suaeda salsa* marsh in the  
464 Yellow River delta, China, with rates ranging from -0.74 to 0.42 mg m<sup>-2</sup> h<sup>-1</sup> (Sun et al., 2013). The  
465 CH<sub>4</sub> emission rates from the rice paddy in the present study were lower than those reported from  
466 continuously and intermittently flooded rice paddies in Nanjing, China, which emitted 1-3 mg m<sup>-2</sup>  
467 h<sup>-1</sup> (Zou et al., 2005). This might be due to temperature differences or differences in soil  
468 characteristics at the two sites.

469 The yearly cumulative CH<sub>4</sub> emissions from Phrag2 were similar to those reported by Xu et al.  
470 (2014) from a coastal saline grass flat dominated by *P. australis* in southeast China (6.28 g m<sup>-2</sup>).  
471 However, markedly higher cumulative CH<sub>4</sub> emissions have been measured from other reed  
472 wetlands, such as 39.5 g m<sup>-2</sup> from a tidal reed marsh in southeast China (Tong et al., 2010) and  
473 65.9 g m<sup>-2</sup> from a restored reed fen in northeastern Germany (Koch et al., 2014). The yearly  
474 cumulative CH<sub>4</sub> emissions from the rice paddy in our study were about six times higher than the  
475 0.54-0.58 g m<sup>-2</sup> measured from rice paddies in eastern China (Zhang et al., 2014) but much lower  
476 than the 57 g m<sup>-2</sup> measured over only two months from a rice paddy in the Philippines (Gaihre et  
477 al., 2014). The *Suaeda* wetlands in our study had no net CH<sub>4</sub> emissions over the sampling period, in  
478 contrast to a *Suaeda glauca* marsh in southeast China which emitted 0.399 g CH<sub>4</sub> m<sup>-2</sup> y<sup>-1</sup> (Xu et al.,  
479 2014).

480 The average ecosystem respiration rates in this study were in a comparable range to those  
481 recorded from coastal saline wetlands in southeast China by Xu et al. (2014). The average CO<sub>2</sub>  
482 emission rates at Phrag1 were somewhat lower than the 569.7 mg m<sup>-2</sup> h<sup>-1</sup> from the *Phragmites*  
483 wetland in their study, whereas the emissions from Phrag2 were higher. Compared to the *Suaeda*  
484 *glauca* marsh in Xu et al. (2014), which emitted on average 248.6 mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>, Suaeda1 and 2  
485 both had higher average CO<sub>2</sub> emissions.

#### 486 **4.5 Conclusions**

487 We aimed at determining which factors are most important under field conditions for controlling  
488 CH<sub>4</sub> and CO<sub>2</sub> emissions from coastal wetlands in order to be able to predict the effects of future  
489 climate change on greenhouse gas emissions from wetlands and potentially to be able to manage  
490 coastal wetlands in a way that minimizes greenhouse gas emissions. Hence, we quantified the CH<sub>4</sub>  
491 emissions and ecosystem respiration from April to November 2012 in five coastal wetlands in the  
492 Liaohe Delta, northeast China, and determined the main controlling factors for the seasonal  
493 variations and the differences among the sites. Over the study period, the two *Suaeda* wetlands  
494 were net CH<sub>4</sub> sinks whereas the *Phragmites* wetlands and the rice paddy were net CH<sub>4</sub> sources.  
495 The *Phragmites* wetlands had the highest climatic impact as they emitted the most cumulative CH<sub>4</sub>  
496 per unit area and the most CH<sub>4</sub> relative to CO<sub>2</sub> compared to the other wetland types. The main  
497 controlling factors for the CH<sub>4</sub> emissions were water table, soil organic carbon, temperature and

498 salinity. Methane emissions are accelerated at high and constant (or managed) water tables and  
499 decrease at water tables below the soil surface, or fluctuating water tables. Methane emissions  
500 are also accelerated at high temperatures and depressed at high salinity levels. Saline wetlands  
501 can, however, emit significant amounts of CH<sub>4</sub> as aerenchymatous wetland plants with deep root  
502 systems can transport CH<sub>4</sub> produced in the deeper soil layers to the atmosphere. The ecosystem  
503 respiration of the wetland communities depends largely on temperature and the plant  
504 aboveground biomass, but soil organic matter content and belowground biomass are also  
505 important. It is, however, necessary to quantify not only the ecosystem respiration, but also the  
506 balance between the net CO<sub>2</sub> exchange and the CH<sub>4</sub> emission to determine if a particular wetland  
507 can be considered to be a net source or a net sink for radiative greenhouse gases. Our study  
508 indicates that the CH<sub>4</sub> emissions from coastal wetlands can be reduced by managing the water in  
509 the wetland in a way that creates fluctuating water tables, including water tables below the soil  
510 surface, as well as by occasional flooding by high-salinity water. However, the effects of potential  
511 water management schemes on the biological communities in the wetlands must be carefully  
512 studied prior to the implementation of the management in order to avoid negative and  
513 undesirable effects on the wetland communities.

#### 514 **Author contribution**

515 S.Y., K.W.K and H.B. designed the study, L.O. and S.Y. performed the field and laboratory  
516 measurements, and L.O. prepared the manuscript with contributions from all co-authors.

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692 **Table 1.** Physical/chemical topsoil characteristics (0-5 cm depth for bulk density, water content and redox  
 693 potential; else 0-4 cm depth) at the five wetland sites (two *Suaeda salsa* wetlands, two *Phragmites australis*  
 694 wetlands and one rice paddy) in the Liaohe Delta, northeast China. Data was collected in 2013 by Siyuan Ye  
 695 et al. (personal communication).

	<b>Suaeda1</b>	<b>Suaeda2</b>	<b>Phrag1</b>	<b>Phrag2</b>	<b>Rice</b>
<b>Bulk density</b> (g cm <sup>-3</sup> )	1.50	1.20	1.07	0.93	1.36
<b>Water content</b> (% of FW)	27	37	41	48	30
<b>Redox potential</b> (mV)	101	24	-127	-91	-82
<b>TN</b> (% of DW)	0.08	0.07	0.17	1.02	0.10
<b>TC</b> (% of DW)	0.95	0.83	1.81	12.59	0.88
<b>Org-C</b> (% of DW)	0.53	0.69	1.67	11.81	0.69
<b>C:N ratio</b>	12.4	12.0	9.8	12.3	8.4
<b>Ca</b> (μg g <sup>-1</sup> )	6735	4215	3817	2103	2239
<b>Cu</b> (μg g <sup>-1</sup> )	9.96	6.78	9.11	7.18	3.44
<b>Fe</b> (μg g <sup>-1</sup> )	282	434	396	343	343
<b>K</b> (μg g <sup>-1</sup> )	849	576	598	892	109
<b>Mg</b> (μg g <sup>-1</sup> )	2043	1120	1395	1687	216
<b>Mn</b> (μg g <sup>-1</sup> )	291	368	308	104	78
<b>P</b> (μg g <sup>-1</sup> )	19.7	27.8	9.9	46.7	37.0
<b>Zn</b> (μg g <sup>-1</sup> )	9.6	11.1	17.8	30.8	8.2

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699 **Table 2.** Results from repeated-measures ANOVAs with the response variables CH<sub>4</sub>-flux and R<sub>eco</sub>,  
700 respectively, the fixed factors Site and Time and their interaction, and the random factor Plot. Gas fluxes  
701 were measured during April-November 2012 from six plots at two *Suaeda salsa* wetlands, two *Phragmites*  
702 *australis* wetlands and one rice paddy in the Liaohe Delta, northeast China. All measurements from April,  
703 May and August were excluded from the analysis due to missing data from some sites.

Response variable	Factor	df	F-ratio	p
CH <sub>4</sub> -flux	Site	4	19.9	<0.001
	Time	4	7.5	<0.001
	Site × Time	16	5.9	<0.001
	Plot (random factor)	25	2.0	0.007
R <sub>eco</sub>	Site	4	23.7	<0.001
	Time	4	379.4	<0.001
	Site × Time	16	55.7	<0.001
	Plot (random factor)	25	1.9	0.010

704 df: degrees of freedom

705 **Table 3.** Results from linear mixed effects models, with CH<sub>4</sub> emission rate and ecosystem respiration rate  
 706 (R<sub>eeco</sub>) as response variables, and the fixed effects Plant species, Biomass, Soil temperature, Water table and  
 707 Salinity. Shown are the coefficients of the fixed effects to be included in equation 1, standard errors of the  
 708 means and p-values.

<b>Response variable</b>	<b>Predictor</b>	<b>Coefficient</b>	<b>SE</b>	<b>p</b>
CH <sub>4</sub> emission rate	Water table	0.0054	0.0014	<0.001
	Soil temperature	0.0017	0.0023	<0.001
	Salinity	-0.0023	0.0030	<0.001
CH <sub>4</sub> emission rate <sup>a</sup>	Water table	0.0071	0.0019	<0.001
	Soil temperature	0.0074	0.0034	<0.001
R <sub>eeco</sub>	Suaeda*Biomass	-1.93 10 <sup>-5</sup>	3.1 10 <sup>-4</sup>	0.003
	Phrag*Biomass	7.1 10 <sup>-4</sup>	2.5 10 <sup>-4</sup>	0.003
	Rice*Biomass	9.2 10 <sup>-4</sup>	3.0 10 <sup>-4</sup>	0.003
	Soil temperature	0.057	0.0042	<0.001
	Salinity	0.0095	0.0044	0.049

709 <sup>a</sup> Only sites with CH<sub>4</sub> emissions >0 included (Phrag1, Phrag2 and Rice).

710 **Table 4.** Mean CH<sub>4</sub> emission and ecosystem respiration rates (R<sub>eco</sub>) with ranges in parentheses, and  
 711 cumulative CO<sub>2</sub> equivalents from CH<sub>4</sub> and CO<sub>2</sub> emissions, respectively, from two *Phragmites australis*  
 712 wetlands and one rice paddy during April-November 2012 in the Liaohe Delta, northeast China. CH<sub>4</sub> fluxes  
 713 are converted to CO<sub>2</sub>-equivalents using a factor of 25. Superscript letters represent significant differences  
 714 (p<0.05) among sites.

Site	CH <sub>4</sub> emission rates (mg m <sup>-2</sup> h <sup>-1</sup> )	R <sub>eco</sub> (mg CO <sub>2</sub> m <sup>-2</sup> h <sup>-1</sup> )	Cumulative CO <sub>2</sub> -equivalents	
			CH <sub>4</sub> (g CO <sub>2</sub> -eqv m <sup>-2</sup> y <sup>-1</sup> )	CO <sub>2</sub> (g CO <sub>2</sub> -eqv m <sup>-2</sup> y <sup>-1</sup> )
<b>Suaeda1</b>	0.01 (-0.31 - 0.44) <sup>a</sup>	278 (-3.6 - 814) <sup>ab</sup>	-0.4	1671
<b>Suaeda2</b>	-0.01 (-0.50 - 0.42) <sup>a</sup>	423 (4.6 - 954) <sup>b</sup>	-1.9	1730
<b>Phrag1*</b>	0.15 (-0.31 - 1.48) <sup>ab</sup>	484 (-14.8 - 1300) <sup>c</sup>	31.1	2963
<b>Phrag2</b>	1.01 (-0.28 - 6.38) <sup>c</sup>	811 (27.4 - 3357) <sup>c</sup>	153.7	4443
<b>Rice</b>	0.75 (-0.27 - 4.63) <sup>b</sup>	532 (-0.2 - 3181) <sup>a</sup>	91.6	3337

715 \* No data from August

716 **Legends to figures:**

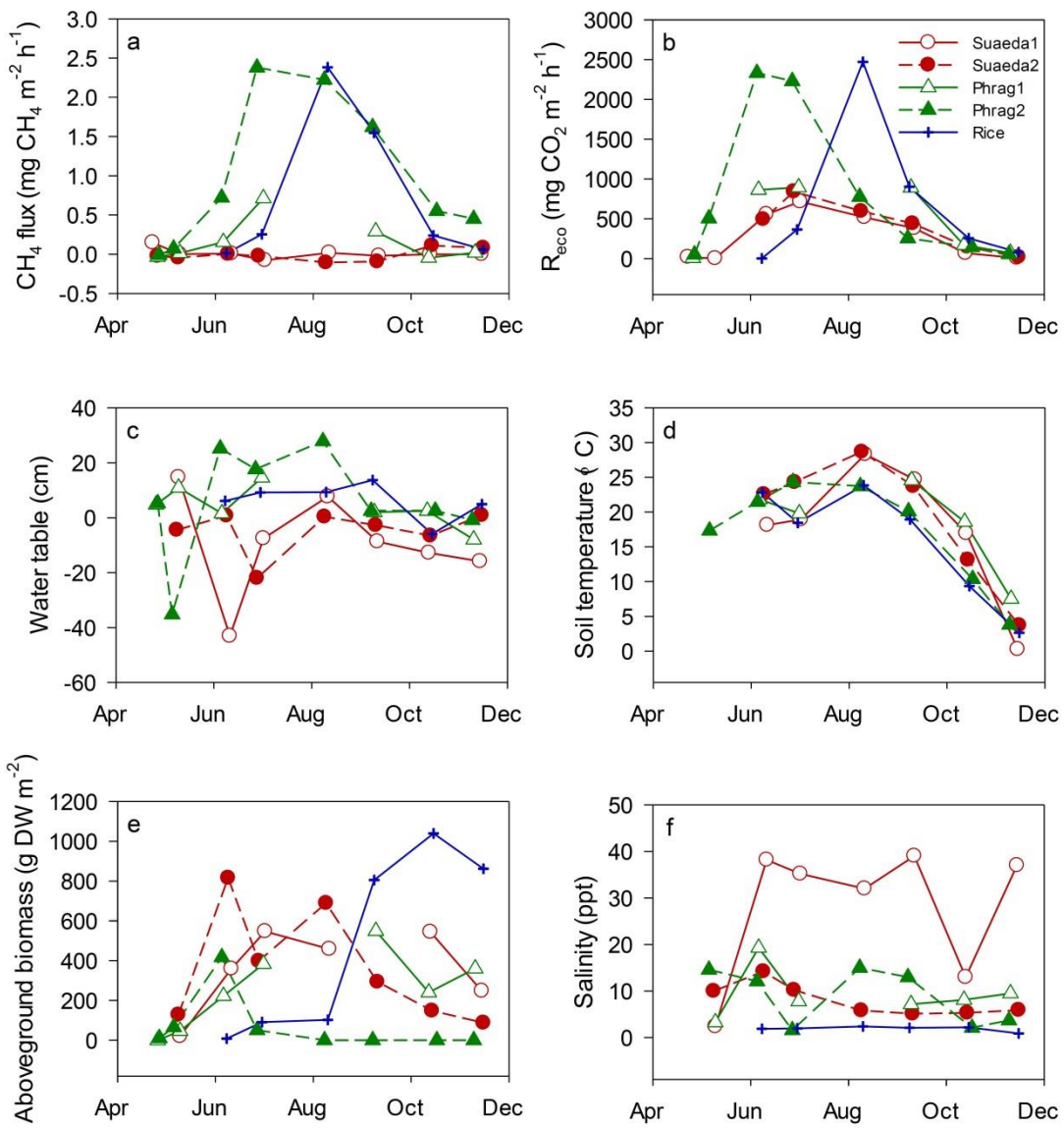
717 **Figure 1.** Seasonal variation in (a) CH<sub>4</sub> emission rates, (b) ecosystem respiration, (c) water table, (d) soil  
718 temperature, (e) aboveground dry biomass and (f) salinity in two *Suaeda salsa* wetlands, two *Phragmites*  
719 *australis* wetlands and one rice paddy during 2012 in the Liaohe Delta, northeast China. Plotted values are  
720 the averages for six plots at each site. Data from Phrag2 is missing in August because it was not possible to  
721 sample due to extreme flooding. Aboveground biomass data from Suaeda1 is missing in September due to  
722 technical issues.

723 **Figure 2.** Cumulative CH<sub>4</sub> emissions during the growing season 2012 from two *Suaeda salsa* wetlands, two  
724 *Phragmites australis* wetlands and one rice paddy during 2012 in the Liaohe Delta, northeast China. The  
725 points represent integrals of the monthly mean values from six plots at each site. Measurements are  
726 missing from Phrag1 in August due to flooding.

727 **Figure 3.** Relationship between CH<sub>4</sub> emission rates and (a) soil temperature, and (b) water table, in two  
728 *Phragmites australis* wetlands and a rice paddy in the Liaohe Delta, northeast China. Data points after  
729 cutting the vegetation at Phrag2 are represented by downward triangles (Phrag2-cut). Measurements were  
730 done from April to November 2012.

731 **Figure 4.** Relationship between salinity and CH<sub>4</sub> emission rates in two *Suaeda salsa* wetlands, two  
732 *Phragmites australis* wetlands and one rice paddy during 2012 in the Liaohe Delta, northeast China. Data  
733 points after cutting the vegetation at Phrag2 are represented by downward triangles (Phrag2-cut).  
734 Measurements were done from April to November 2012.

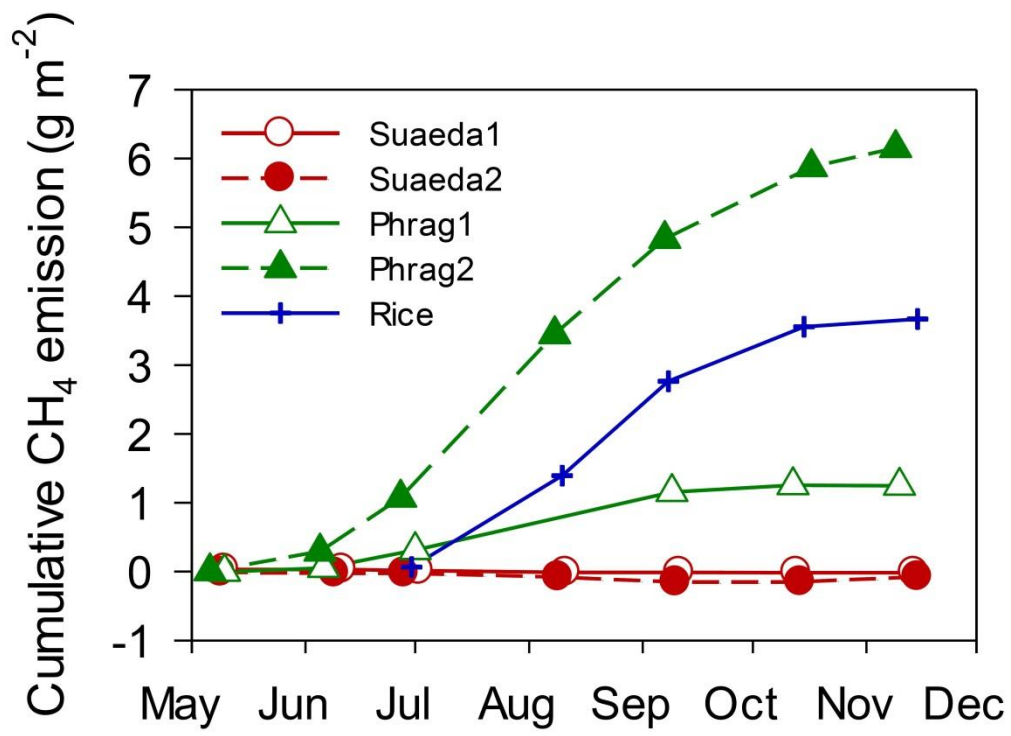
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737 Fig. 1

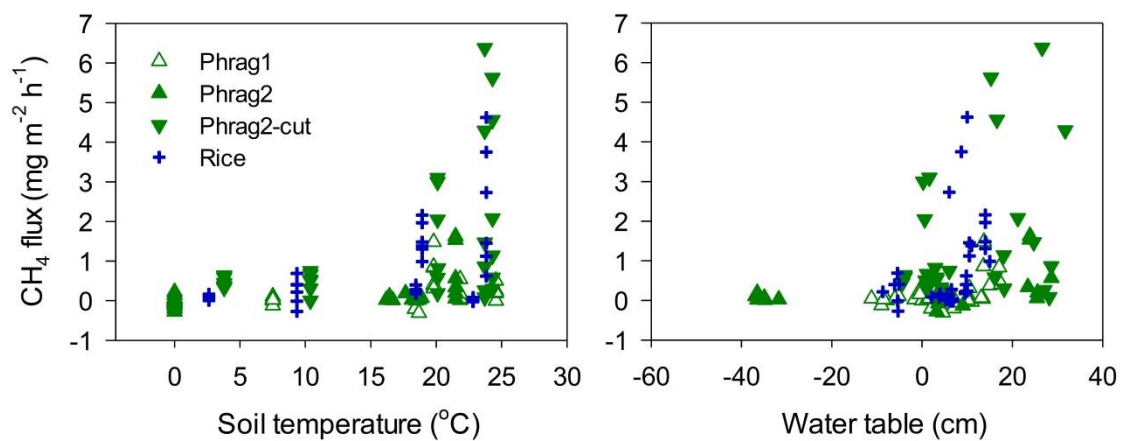
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740 Fig. 2

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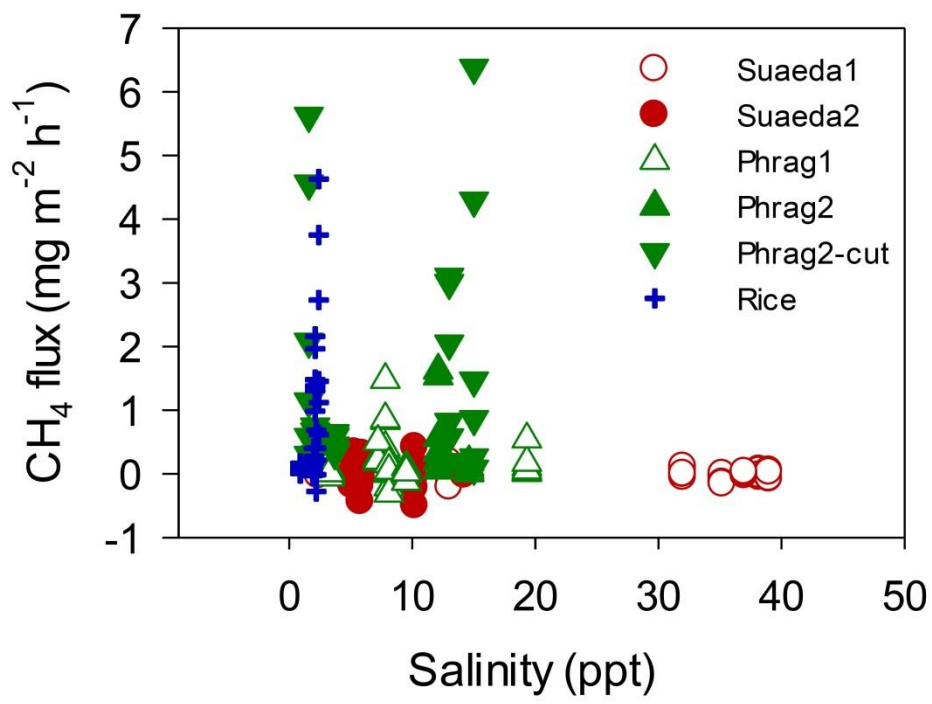


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743 Fig. 3

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746 Fig. 4