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LETTER

Soil greenhouse gas emissions reduce the contribution of mangrove plants to the atmospheric cooling effect

Guangcheng Chen[1,4], **Bin Chen**[1], **Dan Yu**[2], **Nora F Y Tam**[3], **Yong Ye**[2,4] **and Shunyang Chen**[1]

[1] Third Institute of Oceanography, State Oceanic Administration, Xiamen, Fujian, 361005, People's Republic of China
[2] Key Laboratory of the Ministry of Education for Coastal and Wetland Ecosystems, Xiamen University, Xiamen, Fujian, 361102, People's Republic of China
[3] Department of Biology and Chemistry, City University of Hong Kong, Hong Kong SAR, People's Republic of China
[4] Author to whom any correspondence should be addressed.

E-mail: gc.chen@tio.org.cn and yeyong@xmu.edu.cn

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Abstract

Mangrove soils have been recognized as sources of greenhouse gases, but the atmospheric fluxes are poorly characterized, and their adverse warming effect has rarely been considered with respect to the potential contribution of mangrove wetlands to climate change mitigation. The current study balanced the warming effect of soil greenhouse gas emissions with the plant carbon dioxide (CO_2) sequestration rate derived from the plants' net primary production in a productive mangrove wetland in South China to assess the role of mangrove wetlands in reducing the atmospheric warming effect. Soil characteristics were also studied in the summer to examine their relationships with gas fluxes. The soil to atmosphere fluxes of nitrous oxide (N_2O), methane (CH_4) and CO_2 ranged from −1.6 to 50.0 $\mu g\ m^{-2}\ h^{-1}$, from −1.4 to 5360.1 $\mu g\ m^{-2}\ h^{-1}$ and from −31 to 512 $mg\ m^{-2}\ h^{-1}$, respectively, which indicated that the mangrove soils act as sources of greenhouse gases in this area. The gas fluxes were higher in summer than in the cold seasons and were variable across mangrove sites. Gas fluxes in summer were positively correlated with the soil organic carbon, total nitrogen, and ammonia contents. The mangrove plants sequestered a considerable amount of atmospheric CO_2 at rates varying from 3652 to 7420 $g\ CO_2\ m^{-2}\ yr^{-1}$. The ecosystem acted as a source of CH_4 and N_2O gases but was a more intense CO_2 sink. However, the warming effect of soil gas emissions accounted for 9.3–32.7% of the plant CO_2 sequestration rate, partially reducing the benefit of mangrove plants, and the two trace gases comprised 9.7–33.2% of the total warming effect. We therefore propose that an assessment of the reduction of atmospheric warming effects by a mangrove ecosystem should consider both soil greenhouse gas emissions and plant CO_2 sequestration.

1. Introduction

Despite the limited area occupied by mangrove wetlands compared to terrestrial forests (Mcleod *et al* 2011), these highly productive ecosystems are suggested to be globally important in exporting carbon to adjacent coastal areas (Dittmar *et al* 2006, Alongi 2014) and in carbon (C) sequestration in the world's oceans (Chmura *et al* 2003, Mcleod *et al* 2011, Duarte *et al* 2013). Mangroves assimilate atmospheric carbon dioxide (CO_2) into biomass and as detritus in soils; they also trap allochthonous organic carbon during flooded periods, which is then stored in the mangrove soils (Duarte *et al* 2013, Alongi 2014). Mangrove plants sequestrate atmospheric carbon at a global mean rate of 1110–1363 $g\ C\ m^{-2}\ yr^{-1}$, and ~70% of the carbon captured is accumulated in biomass (Bouillon *et al* 2008, Alongi 2009). Recent studies also estimated the global mean rate for soil carbon burial as 163–226 $g\ C\ m^{-2}\ yr^{-1}$ in mangrove wetlands (Breithaupt *et al* 2012, Mcleod *et al* 2011, Alongi 2014). The reduction of the carbon loss in mangrove wetlands and the increasing the existing carbon pools for carbon sequestration are considered important for climate change mitigation (Duarte *et al* 2013).

Numerous studies have recognized mangrove soil as sources of atmospheric greenhouse gases, such as CO_2, methane (CH_4) and nitrous oxide (N_2O), and proved that these gas emissions can be further enhanced by anthropogenic nutrient inputs (Muñoz-Hincapié *et al* 2002, Kreuzwieser *et al* 2003, Allen *et al* 2007, Chen *et al* 2011, Purvaja and Ramesh 2001). Therefore, the direct effect of mangrove wetlands on atmospheric warming is reflected by the exchange of greenhouse gases between the mangrove ecosystem and the atmosphere as it relates to the ecosystem's reduction or contribution to atmospheric radiative forcing (Chmura *et al* 2011).

According to the carbon budget presented by Bouillon *et al* (2008), the mean soil CO_2-C flux of global mangrove represents ~20% of the mangrove net primary production (NPP), which indicates that the soil CO_2 emissions offset 20% of the plant CO_2 sequestration on the global scale. Although the fluxes of CH_4 and N_2O are generally two or three orders of magnitude lower than the CO_2 flux in mangrove wetlands (Chen *et al* 2010), their contributions to global warming could also be substantial and are worthy of attention because they are more stable and exhibit considerably higher radiative forcing than CO_2 (Myhre *et al* 2013). However, the greenhouse gas emissions from the mangrove soils remain poorly characterized, and the extent to which the gas emissions could offset the benefit of plant carbon sequestration is still unclear.

In this study, soil greenhouse gas fluxes were investigated in mangrove wetlands in the Jiulong River Estuary (JRE) in South China, which have been reported to be productive (Lin *et al* 1985, Lu *et al* 1988) and to have rapid mineralization rates of soil carbon and nitrogen owing to the impact of human activities (Alongi *et al* 2005). The warming effect of gas emissions was then balanced with the plant CO_2 sequestration rate to estimate the atmospheric cooling effect of mangrove wetlands based on the exchange of greenhouse gases between the mangrove ecosystem and the atmosphere. We also evaluated the effects of soil characteristics on greenhouse gas emissions. We hypothesize that (1) the greenhouse gas emissions from mangrove soils offset the benefits of mangrove plants in reducing atmospheric radiative forcing and (2) the warming potentials of the trace N_2O and CH_4 may be non-negligible and should be considered in the evaluation of the warming effect of soil gas emissions.

2. Methods

2.1. Study area

The subtropical JRE has a mean annual temperature of 20.9 °C. The tides in this area are semi-diurnal, with an average range of 4 m, and the mangrove soils are primarily composed of silt and clay (Alongi *et al* 2005). Most of the primary mangrove forests in this region were destroyed for aquaculture activity and sea-wall construction. The plantation of *Kandelia obovata* was established in the 1960s and 1980s near Caoputou Village (CPT), located on the south bank to protect the shoreline. Most mangrove forests in the estuary now appear as narrow fringing forests because of destruction.

Because some mangrove-dominated shores were subjected to erosion, *Spartina alterniflora* invasion or garbage accumulation, the current study chose sites that displayed good conditions to eliminate such exogenous impacts. Sampling was performed at three mangrove sites (figure 1, table 1) located at CPT, Xiaguo Village (XG) and on Haimen Island (HMI). The CPT site was a rehabilitated, and now mature, *K. obovata* forest that was planted in 1962 at the high intertidal zone with a high canopy height. The natural XG site was located in the mid-intertidal zone based on its intertidal elevations and the intertidal zonation scheme in the JRE as described by Chen *et al* (2006). The lowest vegetation density and canopy height occurred at the mid-low natural HMI mangrove site.

2.2. Soil-to-atmosphere greenhouse gas fluxes

The soil to atmosphere fluxes of greenhouse gases were sampled in winter, spring, summer and autumn, in the three mangrove sites. All sampling was conducted two hours before the lowest ebb tide during the daytime, and the tidal range and exposure duration were comparable among the sampling days and the three sites.

The gas flux in this study was sampled using the static chamber technique (Chen *et al* 2010). Nine transparent static chambers were placed at each site and inserted 3 cm into the soil between trees in locations without mangrove seedlings, aboveground roots or litter fall. The chambers had a basal area of 0.025 m^2 and a headspace volume over the soil of 1.25 l, with a volume/basal area ratio that is sufficiently small for rapid increases in gas concentrations (Corredor *et al* 1999, Bauza *et al* 2002). The deployment time was set to 30 min, with sampling at 10 min intervals. Gas concentrations were analysed in parallel with a gas chromatography system (7890A, Agilent Technologies, Santa Clara, CA, USA) by comparing their peak areas against an Agilent Greenhouse Gas Checkout Sample, with 600 parts per million (ppm) CO_2, 5 ppm CH_4 and 1 ppm N_2O in nitrogen. The N_2O and CH_4 concentrations were determined with a 63Ni electron capture detector and a flame ionization detector (FID), respectively. The CO_2 concentration was analysed using FID after methanization. During the measurement, the standard was analysed every 15–20 samples. The standard deviations of replicate standard measurements were less than 4% for the three gases.

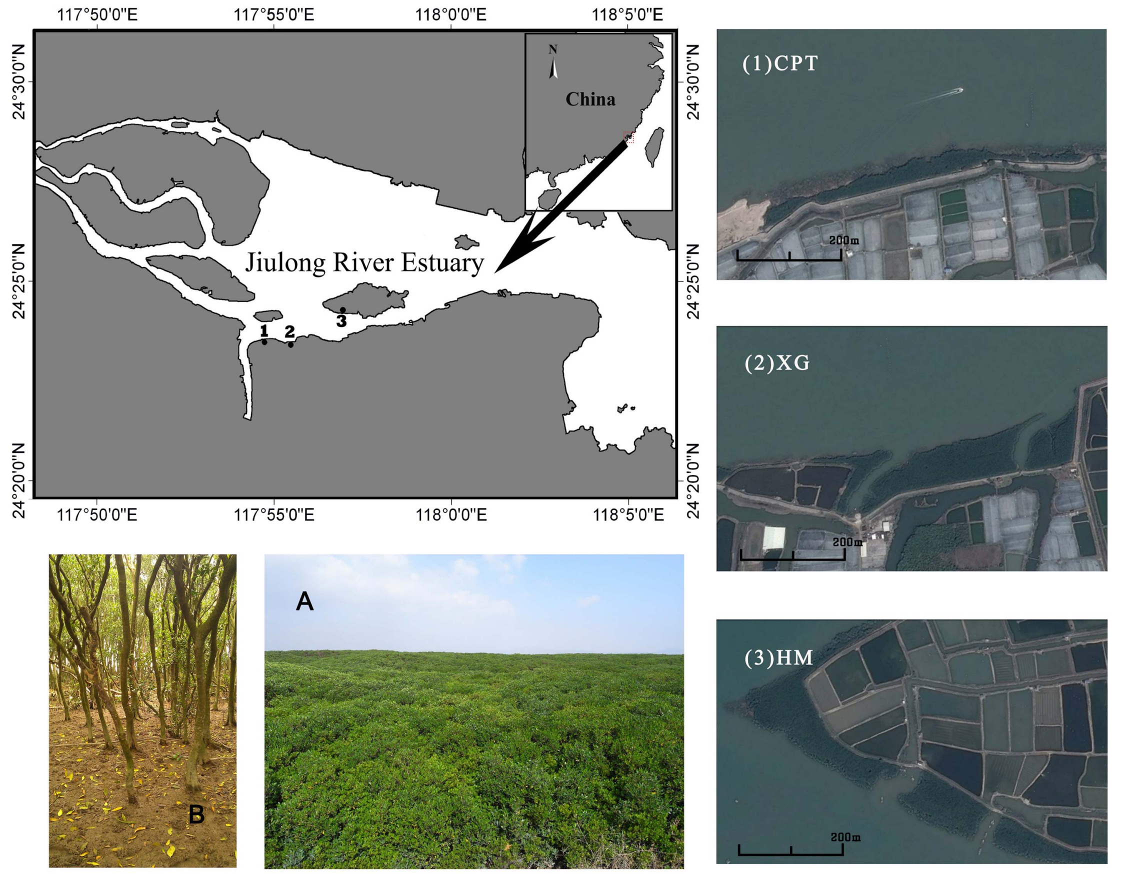

Figure 1. Map of the Jiulong River Estuary, China and a typical scene from the mangrove forest (A and B). Numbers 1–3 indicate the positions of the three sampling sites in this study: 1: Caoputou; 2: Xiaguo; 3: Haimen Island.

Table 1 Vegetation characteristics of the three sampling sites.

	Mangrove sites		
Parameters	Caoputou	Xiaguo	Haimen Island
Location	24.3946N, 117.9119E	24.3934″N, 117.9221″E	24.4067″N, 117.9413E
Canopy height (m)	7.8	6.2	4.2
Tree density (stem m^{-2})	1.0	1.7	0.7
Forest width (m)	~40	~90	~90

2.3. Sampling and analysis of soil

Soil parameters were also measured at these sites during the summer to examine their relationship with gas fluxes because the fluxes have been found to be higher during the summer in subtropical mangroves (Chen *et al* 2012). The soil redox potential (E_h) under the chamber was measured using a pH/E_h meter (WP-81, TPS, Australia) after gas sampling at a depth of 5 cm from the surface. Soils, to a depth of 5 cm, were collected using a steel tube (inner diameter 1.75 cm) with a sharpened open end to estimate the bulk density. Independent soil cores (6 cores for each mangrove site) were collected to a depth of 15 cm using hand-held PVC corers. Soil organic carbon (OC) concentration was analysed using the rapid dichromate oxidation procedure. Total Kjeldahl nitrogen (TKN), after Kjeldahl digestion, ammonia (NH_4^+-N) and nitrate (NO_3^--N), in a potassium chloride (2 M) extract, were measured using a Continuous Flow Analyzer (Futura II, Alliance Instruments, France). All soil analyses were based on the soil analysis methods described by Page *et al* (1982), and the data were expressed in terms of the 105 °C oven-dried weight.

Soil porewater salinity was measured using a pocket refractometer (Atago PAL-06 S, Japan) at the seaward fringe of each site with triplicates because porewater samples were not available for all sample plots. Such measurements do not reveal the salinities within the wetlands but reflect the salinity gradient among the three sites.

2.4. Plant CO_2 sequestration rate

The plant CO_2 sequestration rate was calculated from the NPP using the following formula:

$$R_{CO_2} = \text{NPP} \times \text{C}_{\text{mangrove}} \times 44/12$$

where R_{CO_2} is the plant CO_2 sequestration rate (g CO_2 m^{-2} yr^{-1}), NPP is the net primary production (g m^{-2} yr^{-1}), C_{mangrove} is the carbon content of mangrove plants (%), and 44/12 is the formula weight ratio of CO_2 to C.

The mangrove NPP was estimated using the litter fall technique (Teas 1979), which postulates that 1/3 of mangrove NPP is returned as litter fall. This rapid and direct method was also applied in other studies (Lee 1990, Alongi 2009), but its accuracy depends on the availability of a good conversion factor of litter production to NPP (Odum *et al* 1982). In this study, we applied a conversion factor 2.75 derived from previously reported NPP data and the concurrent litter fall production of *K. obovata* in the JRE (Lin *et al* 1985). The mean plant carbon content was 47% for *K. obovata* in the JRE (Zheng *et al* 1995).

Litter-fall samples were collected using metal-framed litter traps ($\Phi = 70$ cm, 30 cm in depth). Nine traps were placed randomly under canopies at similar heights above the maximum tide level at each site. The trap contents were collected monthly and sorted as leaf, wood and reproduction (flowers and propagules) components and dried at 60 °C to a constant weight. The litter fall production was expressed as the total dry weight of these components.

2.5. Atmospheric cooling effect of a mangrove ecosystem

The gas fluxes were converted to CO_2-equivalent fluxes to indicate their respective warming effect using the global warming potential (GWP) of each gas. The GWPs were 1, 34 and 298 for CO_2, CH_4 and N_2O, respectively, over a 100-year timeframe according to Myhre *et al* (2013). The annualized warming effect of gas emissions at each site was compared to the CO_2 sequestration rate of plants to estimate the ecosystem effect. Net ecosystem production (NEP) of the three mangrove sites was also estimated by subtracting the soil respiration rate from NPP, and the soil respiration rate was calculated as the sum of the CO_2-C and CH_4-C fluxes.

2.6. Statistical analysis

The normality of variables was assessed using the Kolmogorov-Smirnov test, and gas fluxes that did not follow a normal distribution were transformed to improve normality and homoscedasticity prior to analysis. A two-way ANOVA was used to test the differences in greenhouse gas fluxes among the four seasons and the three sites. If the difference was significant ($p < 0.05$), a post-hoc Tukey test was used to determine the difference. Differences in the litter fall production and soil characteristics were compared using one-way ANOVA. Pearson correlation coefficients were calculated to determine the relationships between soil properties and gas fluxes in the summer. All statistical analyses were performed using PASW Statistics for Windows, Version 18.0 (SPSS Inc., Chicago, IL, USA).

3. Results and discussion

The present study further demonstrates that mangrove soils can be sources of greenhouse gases (figure 2). The soil gas fluxes at these three sites were −1.6 to 50.0 $\mu g\ m^{-2}\ h^{-1}$, −1.4 to 5360.1 $\mu g\ m^{-2}\ h^{-1}$ and −31 to 512 mg m^{-2} h^{-1}, for N_2O, CH_4 and CO_2, respectively, which fell within the ranges from −19.8 to 1179.2 μg N_2O m^{-2} h^{-1}, from −96.8 to 82697.6 μg CH_4 m^{-2} h^{-1} and from less than −190 to 442 mg CO_2 m^{-2} h^{-1} that were previously reported for other mangrove forests (Bouillon *et al* 2008, Chauhan *et al* 2008, Chen *et al* 2010 2014, Murray *et al* 2015). Similar to previous studies (Allen *et al* 2011, Chen *et al* 2010, 2012), gas fluxes in this study varied spatially and seasonally (figure 2). The XG site had a higher soil N_2O flux than the other two sites ($F = 10.63$, $p = 0.000$), both of which had similar fluxes. The highest N_2O flux was measured during the summer, and the lowest was measured during the winter and autumn ($F = 17.21$, $p < 0.001$). CH_4 flux also showed significant spatial ($F = 15.36, p < 0.001$) and seasonal ($F = 26.03$, $p < 0.001$) variations, and significant interactions were also found between these factors ($F = 3.83$, $p < 0.001$), which indicated that their variation was site- or season-specific (figure 2). For CO_2, the flux significantly varied among the mangrove sites ($F = 10.24$, $p < 0.001$) and the four seasons ($F = 73.25, p < 0.001$), and their interaction was significant ($F = 4.42$, $p < 0.01$). Sinks of CO_2 were measured in the winter at the three sites, but the soils in the warmer seasons acted as significant CO_2 sources.

The spatial variations in greenhouse gas fluxes from mangrove soils could be partially attributed to the spatial differences of the soil characteristics because the fluxes are related to soil properties, including OC and nitrogen concentrations, bulk density, salinity and redox potential (Allen *et al* 2007, Chen *et al* 2010, 2012, Purvaja and Ramesh 2011). In our summer investigation, the higher fluxes of the three gases were attributed to higher soil OC, TKN and NH_4^+-N concentrations in the mangrove soils (figure 3 and table 2). Positive soil E_h in the mangrove soil and a significant correlation between N_2O flux and soil NH_4^+-N concentration indicated the importance of soil nitrification that is responsible for the variability of N_2O flux. Like other studies (Allen *et al* 2007, Chen *et al* 2010), high soil NH_4^+-N concentrations enhanced CH_4 emissions in this study, probably because of the inhibitory effect of soil NH_4^+-N on CH_4 oxidation under high NH_4^+-N concentrations (Bosse *et al* 1993). The lower soil CH_4 flux and higher porewater salinity at HMI (figure 3) were consistent

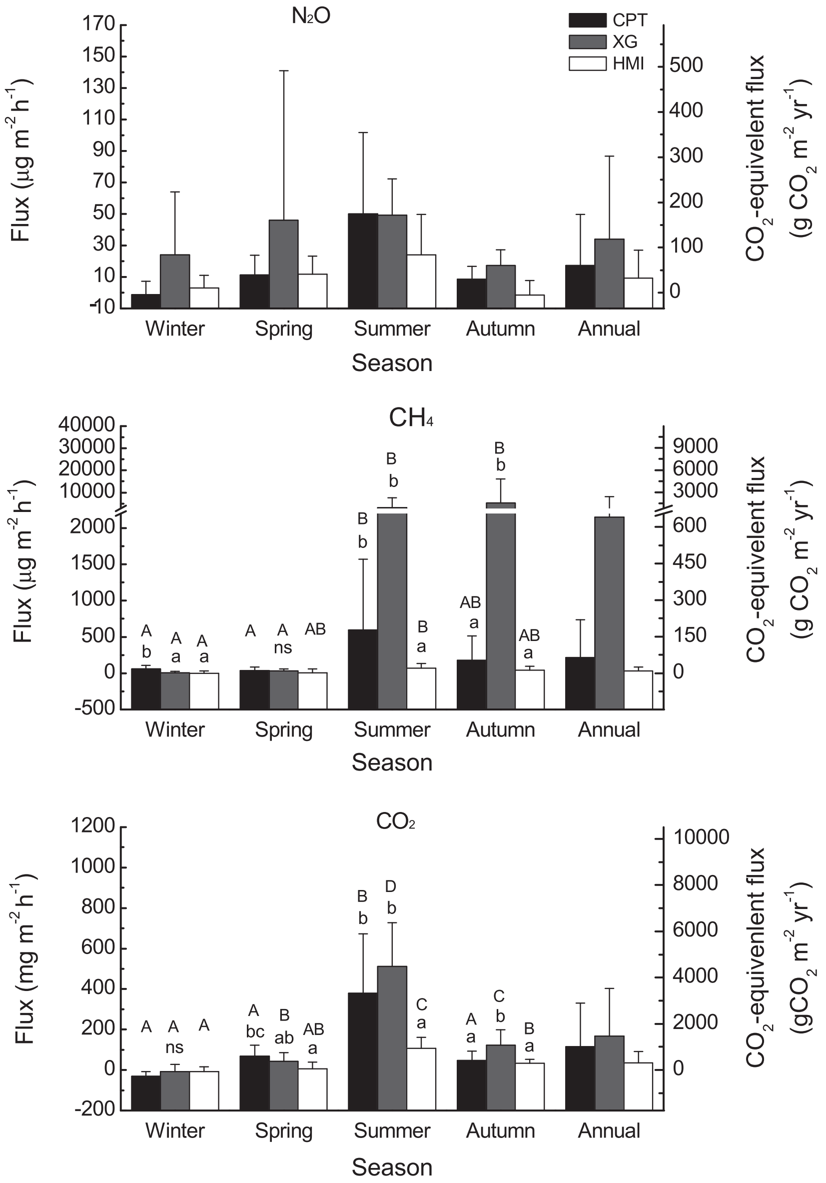

Figure 2. Soil to atmosphere greenhouse gas flux (mean ± SE, $n = 9$ for the seasonal fluxes and 36 for the annual mean fluxes) at the mangrove sites in the Jiulong River Estuary. Figure 2 uses the same abbreviations as figure 1. In each season, different letters (lower case letters) indicate significant differences among the three mangrove sites according to the ANOVA test. For each mangrove site, different letters (capital letters) indicate significant differences among the four seasons.

with the inhibitory effect of salinity on CH_4 emission from coastal soils because the presence of high sulfate allowed sulfate-reducing bacteria to outcompete methanogens for energy resources (Biswas *et al* 2007, Poffenbarger *et al* 2011, IPCC 2014).

The subtropical *K. obovata* mangrove forest in the Jiulong River Estuary had litter fall production ranging from 771 g m^{-2} yr^{-1} to 1565 g m^{-2} yr^{-1} (table 3), and the leaf fall and reproduction components accounted for 44% and 41% of the total production, respectively. Owing to its lower leaf and twig production, the litter fall production and NPP at HMI were lower than those of the other two sites. NPP estimated from litter fall production was 2119–4306 g m^{-2} in the three sites, close to the quantities reported in tropical regions and higher than the global mean production (Bouillon *et al* 2008). This is consistent with the summary presented by the IPCC (2014), which showed that certain subtropical mangroves have higher growth rates than those of the tropical regions. The high NPP and low carbon gas emissions from soil in the current study indicated that the mangrove wetlands have strong sequestration capacity for atmospheric CO_2 at the ecosystem scale. The three mangrove sites in the JRE had NEP varying from 912 to 1746 g C m^{-2} yr^{-1}, which is comparable to the NEP of the western Florida Everglades mangrove forest (1170 gC m^{-2} yr^{-1}, Barr *et al* 2010) and higher than the *Rhizophora mangle* forest (561 g C m^{-2} yr^{-1}) in Puerto Rico (Golley *et al* 1962). The mean NEP of the three sites in the JRE, 1358 g C m^{-2} yr^{-1}, was higher than the global mean value of 1100 g C m^{-2} yr^{-1} (Bouillon *et al* 2008).

When both plant CO_2 sequestration and soil gas emissions were considered, mangrove wetlands were

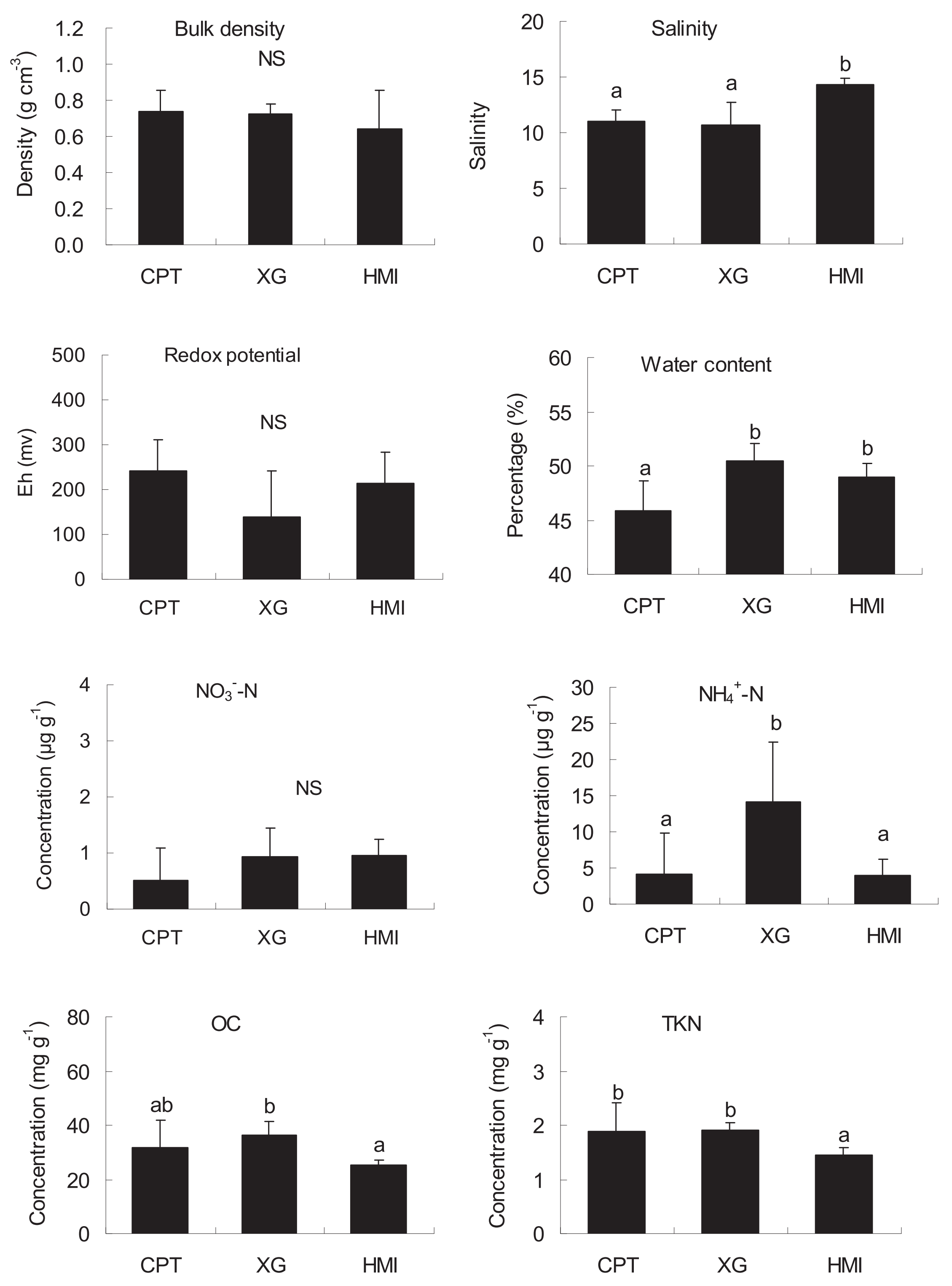

Figure 3. Soil characteristics (mean ± SE, $n = 6$) at the mangrove sites in the Jiulong River Estuary. Figure 3 uses the same abbreviations as figures 1 and 2. Different letters indicate significant differences among the three mangrove sites according to the ANOVA test.

small sources of CH_4 and N_2O and significant CO_2 sinks in this study (figure 2, table 4). Although CH_4 emissions were significant in the estuarine mangrove wetlands, they accounted for a small proportion (0.2–3.4%) of the soil gaseous carbon emissions (figure 2, table 4). If considering their warming effect, soil gas emissions had total CO_2-equivalent fluxes ranging from 340 to 2200 g CO_2 m^{-2} yr^{-1} for the three sites, accounting for 9.3%–32.7% of the plant CO_2 sequestration rate in this study (table 4). The higher total CO_2-equivalent flux at the XG site was attributed to the higher fluxes of CO_2 and CH_4 in this site than the other two sites. The spatial variation of the total CO_2-equivalent flux was related to the soil NH_4^+-N, OC and TKN concentrations (table 2). The mean reduction effect of the JRE mangrove sites on

Tablee 2. Pearson correlation coefficient values (*r*) between soil properties and summer fluxes of greenhouse gases in the Jiulong River Estuary.

	Fluxes of gases			
Soil parameter	N_2O	CH_4	CO_2	Total CO_2-equivalent flux
Redox potential	−0.323	−0.126	−0.130	−0.157
Bulk density	0.406	0.311	0.152	0.160
Water content	0.424	0.329	0.175	0.359
NH_4^+-N	0.575*	0.730**	0.618*	0.720**
NO_3^--N	−0.199	0.008	−0.205	−0.175
OC	0.756***	0.838***	0.713**	0.831***
TKN	0.812***	0.541*	0.724**	0.789***

NH_4^+-N: ammonia, NO_3^--N: nitrate, OC: organic carbon, TKN: total Kjeldahl nitrogen. *, ** and *** indicate significant *r*-value at $p < 0.05$, 0.01 and 0.001, respectively ($n = 18$). No correlation was calculated between porewater salinity and gas flux because the porewater samples were collected outside of the sampling areas.

Table 3. Litter fall production and net primary production ($g\ m^{-2}\ yr^{-1}$) at the three mangrove sites in the Jiulong River Estuary.

Mangrove sites	Leaf	Twig	Reproduction	Total	NPP
CPT	683 ± 101^{a}	241 ± 105^{a}	641 ± 234^{a}	1565 ± 246^{a}	4306 ± 676^{a}
XG	692 ± 86^{a}	267 ± 164^{a}	458 ± 177^{a}	1417 ± 189^{a}	3899 ± 519^{a}
HMI	275 ± 121^{b}	52 ± 72^{b}	444 ± 160^{a}	771 ± 143^{b}	2119 ± 393^{b}
Mean	550 ± 222	187 ± 151	514 ± 207	1251 ± 355	3441 ± 1098

CPT: Caoputou; XG: Xiaguo; HMI: Haimen Island; JRE: Jiulong River Estuary; NPP: Net primary production. Different superscript letters present in a column indicate a significant difference among the three mangrove sites. Data are given as the mean ± SE of each site or the three sites ($n = 9$ for each site and $n = 36$ for JRE, as in table 3).

atmospheric warming was estimated as 4708 g CO_2 m^{-2} yr^{-1}, suggesting that mangrove wetlands in this region are important sinks of atmospheric CO_2 in terms of radiative forcing.

Previous studies have reported the diurnal fluctuations of gas fluxes from mangrove soils (Chang and Yang 2003, Allen *et al* 2007). In this study, the annual fluxes were estimated by extrapolating the seasonal fluxes of 9 sampling points at each site without consideration of the diurnal variations in the gas fluxes. Some other studies also used this extrapolation method for gas emission rates in mangrove wetlands (Chauhan *et al* 2008, Krithika *et al* 2008, Lovelock 2008, Bulmer *et al* 2015). Although such extrapolations lead to an error in annual gas emission rates, we consider that this error did not alter the overall conclusion the warming effect of soil gas emissions would substantially reduce the plant CO_2 sequestration in this study. This is because the diurnal fluctuation patterns of the gas fluxes are variable across different months and sampling stands (Chang and Yang 2003, Allen *et al* 2007), and these variabilities are likely to reduce the errors in our annual emission rates. However, the errors for such estimations and the diurnal variation patterns of gas fluxes warrant further study. In the present study, the CO_2 fluxes measured in the chambers placed over a clear mangrove floor (without pneumatophore, seedlings or litter fall) were more likely to represent microbial metabolisms (Komiyama *et al* 2008, Chen *et al* 2012). If the CO_2 emissions from other sources were considered, i.e. decomposition of litter fall and dead wood as important carbon pools in the mangroves (IPCC 2014), the warming effect of the gas emissions from the mangrove floor would be more substantial.

We measured lower primary production at HMI (table 3) accompanied by lower gas emission rates than the other two mangrove sites in this study. Similarly, the soil respiration rate was found to be correlated with litter fall production over a large range of latitudes extending from 27°N to 37°S (Lovelock 2008). This pattern suggests that the greater amount of CO_2 sequestrated by mangroves, the more substantial the warming effect of soil greenhouse gas emissions might be. Globally, the mangrove NPP decreases with increasing latitude, and the highest litter fall rates occur in the tropical areas (Bouillon *et al* 2008, Alongi 2009). Other studies reported low greenhouse gas emissions from soils in tropical mangrove wetlands (Chen *et al* 2014, Nóbrega *et al* 2016). These results suggest that tropical mangrove wetlands, which represent most global mangroves (Giri *et al* 2011), could be more relevant to reducing atmospheric radiative forcing and their role deserves detailed studies.

Despite their low fluxes compared with CO_2, the contributions of CH_4 and N_2O gases is non-negligible (9.7%–33.2%) to the total warming effect of soil gas emissions in the mangrove wetlands (figure 2).

Table 4. Net ecosystem production and the mitigating effects of wetlands on global warming in the Jiulong River Estuary.

Mangrove sites	Soil C-gas flux (g C m^{-2} yr^{-1})	Net primary production (g C m^{-2} yr^{-1})	Net ecosystem production (g C m^{-2} yr^{-1})	Plant CO_2 sequestration rate (g CO_2 m^{-2} yr^{-1})	CO_2 equivalent flux[a] (g CO_2 m^{-2} yr^{-1})	Ecosystem cooling effect[b] (g CO_2 m^{-2} yr^{-1})
CPT	278 ± 515	2024 ± 317	1746	7420 ± 1165	1125 ± 2050 (9.8%)	6295 (15.2%)
XG	415 ± 572	1832 ± 244	1417	6719 ± 894	2200 ± 3032 (33.2%)	4519 (32.7%)
HMI	84 ± 133	996 ± 185	912	3652 ± 677	340 ± 513 (9.7%)	3312 (9.3%)
Mean	259 ± 468	1617 ± 516	1358	5930 ± 1893	1222 ± 2249(23.8%)	4708 (20.6%)

CPT: Caoputou; XG: Xiaguo; HMI: Haimen Island; JRE: Jiulong River Estuary. Data are given as the mean ± SD for each site or for the JRE (for gas flux, $n = 36$ for each site and $n = 108$ for JRE).

Net primary production was derived from litter fall production (table 2) and the carbon content in mangrove plants (47%, Zheng *et al* 1995) in the JRE. Net ecosystem production was estimated using the difference between NPP and the soil respiration rate, i.e., soil C-gas flux (the sum of CO_2-C and CH_4-C fluxes). The ecosystem cooling effect was estimated by comparing the annualized warming effect of gas emissions against the CO_2 sequestration rate of plants.

[a] Values in the brackets represent the proportion of N_2O and CH_4 gases to the total CO_2-equivalent flux.

[b] Values in the brackets represent the proportion of the warming effect associated with gas emissions relative to the plant CO_2 sequestration rate.

The emissions of these two gases could be largely enhanced from mangrove soils subjected to anthropogenic nutrient inputs (Muñoz-Hincapié *et al* 2002, Chen *et al* 2011). Higher emission rates of N_2O and CH_4 than those in this study have been reported from mangrove soils in the Futian mangrove in South China, which receives anthropogenic nutrient inputs, and these two gases contribute twice the global warming potential of CO_2 (Chen *et al* 2010). Because the soil fluxes of CH_4 and N_2O are still poorly quantified from mangrove soils (Chen *et al* 2010, Murray *et al* 2015), they should receive additional attention and be documented, in addition to CO_2 fluxes, to quantify the global warming potential of soil gas emissions from mangrove wetlands, especially for mangroves receiving exogenous nutrients.

Other studies in salt Marshes also quantified the potential global warming feedback based on the soil carbon burial rate and non-CO_2 gas emission rates (e.g., Chmura *et al* 2011, Yuan *et al* 2015). In salt marshes, the carbon accumulation in the biomass through plant growth is roughly balanced by losses through grazing, decomposition and fire (IPCC 2006, 2014). Unlike the salt marshes, the majority of carbon captured by mangrove plants is stored in biomass. Here, we further estimated the potential global warming feedback of the JRE mangrove wetland using the CO_2-equivalent flux of non-CO_2 gases in this study (290 g CO_2 m^{-2} yr^{-1}) and the soil burial rate (404.4 g C m^{-2} yr^{-1}) reported by Alongi *et al* (2005) for the JRE mangrove wetland, with a mangrove biomass accumulation rate (1.75 times litter fall production in this study) taken into account as well. The potential global warming feedback of the JRE mangrove wetland, ~4850 g CO_2 m^{-2} yr^{-1}, was higher than those in northern and north-western Atlantic salt Marshes estimated in the growing season (574–1000 g CO_2 m^{-2} yr^{-1}, Chmura *et al* 2011) and in the marshes of eastern China (114–1130 g CO_2 m^{-2} yr^{-1}, Yuan *et al* 2015), indicating that the mangrove wetland plays a substantial role in global warming feedback.

4. Conclusions

The current study showed that mangrove soils are sources of greenhouse gases, and their warming effect partially offset the benefit of plant CO_2 sequestration in reducing the atmospheric warming effect. Therefore, we propose that any assessment of the reduction effect that mangrove wetlands have on atmospheric warming should consider soil greenhouse gas emissions. The contributions of soil CH_4 and N_2O emissions to the warming effect should not be ignored, and CO_2 emissions from other aboveground sources should also be considered. The current study assessed the role of the mangrove wetlands in reducing the atmospheric warming effect based on the greenhouse gas exchanges between the mangrove ecosystem and the atmosphere. Further assessment of the potential of the mangrove wetland in global warming feedback is necessary, with both soil greenhouse gas emissions and the ecosystem's carbon sequestration considered.

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